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Region-county characteristic of spatial-temporal evolution and influencing factor on land use-related CO_2 emissions in Chongqing of China, 1997–2015

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ABSTRACT

The dependence of county industry on high CO_2 emission industries makes it difficult to balance the development of county economy and CO_2 emission reduction. Therefore, this article attempts to study on the spatial-temporal evolution and influencing factor on land use-related CO_2 emissions at region-county level to promote county economy from CO_2 source to CO_2 sink. 9 regions and 38 counties in Chongqing of China were thus selected as study objects. Based on land use data, land use-related CO_2 emissions were estimated using direct and indirect CO_2 emission models for the period 1997–2015. On this basis, the space-time patterns were revealed from two scales of region and county. And the main factors influencing CO_2 emissions according to land use were revealed based on Logarithmic Mean Divisia Index (LMDI) and geographic detector analysis (GDA), respectively. The results show that: 1) at regional scale, CO_2 emissions of different regions all greatly improve in which southeastern ecological protection and development area showed the largest increase. Increases in *per capita* CO_2 emissions in two-wing (suburban) areas are higher than those in downtown and surrounding-downtown areas. 2) at regional scale, the influences of various decomposed factors on the change of CO_2 emissions fluctuate. The effect of population shows an insignificant influence on CO_2 emissions. Economic development greatly influences CO_2 emissions. Additionally, energy consumption shows a significant inhibitory effect on CO_2 emissions while energy mix exhibits significant hysteresis. 3) at county scale, heavy CO_2 emissions are concentrated in core urban areas; moderate and mild emissions occur mainly in the main urban expansion area, the region around the main urban areas, and in regional hub cities; low emissions are mainly concentrated in the Wuling mountainous area in southeast Chongqing and the Three Gorges Reservoir area in northeast Chongqing. 4) at county scale, the main influences on land use-related CO_2 emissions are total energy consumption, *per capita* GDP, and urbanization rate. Minor influences include population size, proportion of secondary and tertiary industries, and proportion of land used for construction.

1. Introduction

Since the middle of the 20th century, the atmospheric carbon dioxide (CO_2) concentration has increased continuously due to human activities, and this has become the main driver of global warming (Ang and Liu, 2006; Cheng et al., 2014). Land use changes according to human activities and is an important factor influencing global climate change and the carbon cycle. All kinds of human energy consumption and industrial activities cause mass CO_2 emissions, and are closely related to land use mode and intensity, and these activities are finally implemented to land use space (Alkimim and Clarke, 2018; Zhao et al., 2010). The carbon cycle can be changed by reinforcing land use regulations and optimizing land use modes. This contributes to lowering CO_2 emissions, enhancing the carbon fixation ability of vegetation, reducing atmospheric CO_2 concentrations, and positively influencing global climate change. Therefore, socioeconomic low-carbon transition and sustainable development can be improved by in-depth discussions about the interaction between land use and

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CO_2 emissions, and by studying the CO_2 emissions of different land use modes. Establishment of new regional ecological civilization construction pattern will be of great strategic importance and practical value.

To assess the CO_2 emissions of different modes of land use, domestic (Chinese) and foreign scholars have carried out a series of related studies from different perspectives. As land use/land cover change is a hot research topic in the field of global climate change at present, many researchers have established CO_2 emission models at global and national scales (Lawrence et al., 2018; Novaes et al., 2017; Quesada et al., 2018). Based on different scenarios mode, they evaluate the impacts of future land-use and land cover changes (LULCC) on terrestrial carbon cycle. And LULCC is considered to be the dominating driving force of future C changes in regions like South America and the southern part of Africa. Moreover, some researchers have discussed spatial and temporal CO_2 emission changes caused by changes in land cover and terrestrial ecosystems (Fang et al., 2007; Houghton, 1999; Houghton and Hackler, 2003; Lai et al., 2016; Zhu et al., 2019). Especially, these studies analyze the spatio-temporal variation of vegetation and soil carbon storage due to the land-use category conversion and land management. Results demonstrate a significant contribution to CO_2 emissions because of urban expansion. Other scholars have established the CO_2 emission coefficients of different land use types based on land use mode in the IPCC greenhouse gases list. Spatial and temporal differences in the CO_2 emissions of various land use types at different scales have been investigated through direct computing methods or with reference to the energy consumption analysis method (Chuai et al., 2012(a); Chuai et al., 2012(b); Zhao et al., 2011). This has revealed the relationship between land use change and CO_2 emissions (Hao et al., 2015; Xu et al., 2016·Zhou et al., 2015). Meanwhile, scholars have also discussed the influencing factors based on analyses of spatial and temporal changes in CO_2 emissions according to land use (Cheng et al., 2014; Sun et al., 2015). These studies calculate the amount of CO_2 emissions by mainly using the data of land use and energy consumption of different regions at provincial level. Some measures are also proposed both from reducing CO_2 emissions and increasing CO_2 absorptions.

Recent studies have analyzed spatial and temporal differences in the CO_2 emissions of different land use types at different scales. Due to data acquisition limitations related to the energy consumed on construction land, many studies have concentrated on the CO_2 emissions of land use and its variability at national or provincial scales (Cui et al., 2018; Xie et al., 2019; Zhang et al., 2018), but few studies have concentrated on the CO_2 emissions of land use and its variability at regional or county scales. Moreover, some studies have conducted related CO_2 emissions analyses within different types of land use, and assessed CO_2 emissions mainly based on energy consumption data. While analyses of the temporal and spatial variations in the CO_2 emissions of various land use types have been profound, few studies have focused on their main influencing factors. County space is the most basic regional unit of economic and social development in China. The economy development in most counties is highly dependent on the resources and has a single industrial structure. In the process of urbanization, on the one hand, due to the unbalanced industrial structure, it has become an important source of CO_2 emissions; on the other hand, due to the main role of agriculture, it has huge CO_2 sink potential. The dependence of county industry on high CO_2 emission industries makes it difficult to balance the development of county economy and CO_2 emission reduction. Therefore, the study on CO_2 emissions of land use at county level is helpful to promote county economy from CO_2 source to CO_2 sink. Chongqing is the only municipality directly under the central government in the middle and western regions with a provincial architecture in China. The spatial difference of economic development at county level is very significant. Chongqing was thus selected in this study, and 9 regions and 38 counties within Chongqing were taken as the basic study units. From two scales of region and county, changes in CO_2 emissions according to different types of land use were recorded over a long time period from 1997 to 2015. And the main factors influencing CO_2 emissions according to land use were revealed based on Logarithmic Mean Divisia Index (LMDI) and geographic detector analysis (GDA), respectively. This study will help to formulate scientific and reasonable regional CO_2 emission reduction policies. It also provides scientific basis for the formulation of low-carbon economic strategy based on the optimization of land use structure in Chongqing.

2. Data sources and methods

2.1. Study area

At the eastern edge of the Sichuan Basin (Fig. 1), Chongqing City (105° 17′–110° 11′ E, 28° 10′–32° 13′ N) is located the transitional zone between the Qinghai-Tibet Plateau and the middle and lower reaches of the Yangtze River. It is adjacent to Hubei and Hunan in the east, bordered by Guizhou in the south, connecting with Sichuan in the west and to Shanxi in the north. It is a strategic industrial and commercial city and land/water transportation junction in southwestern China. It is the largest economic center in the upper reaches of the Yangtze River and joins the developed eastern region with the western region, which has abundant natural resources. Therefore, it has a superior geographic position. The region under the jurisdiction of Chongqing is 470 km in length from east to west, and 450 km in width from south to north. It covers an area of 82,400 km^2 and is divided into 38 districts and counties. It has the largest area and population in all municipalities. The municipality is under direct control of the central government, and integrates a

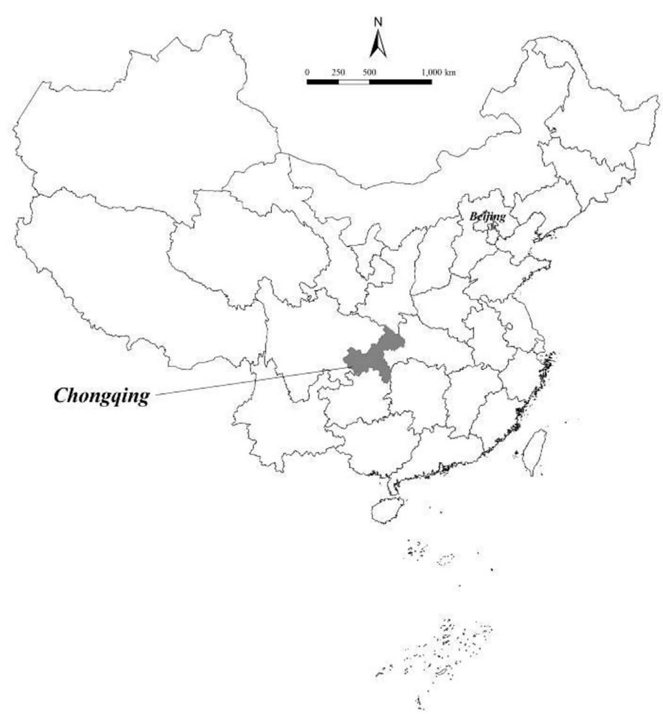

Fig. 1. The position of Chongqing.

metropolis, large villages, large reservoir areas, large mountainous areas and is inhabited by several ethnic groups. The whole city has a large topographic relief with diversified geomorphic types. The mountainous area of the whole city is 62,500 km^2, which occupies 75.94% of the total territorial area. The hilly area is 15,000 km^2, which occupies 18.23% of the total territorial area. The area of flat dams and highlands only occupies 5.83% of the total territorial area. The permanent residential population in 2016 was 30,484,300, the urbanization rate was 62.6%, and gross regional domestic product was 1,755,876 million yuan. At present, Chongqing is in the critical period of economic development. Due to rapid development of urban-rural economy, it leads to a great pressure on environmental protection and emission reduction. Especially, Chongqing has a large proportion of heavy industry and traditional energy-intensive industries. So it is selected as one of the first low-carbon pilot cities in China. At the same time, Chongqing is a municipality with the medium provincial and territorial framework. Due to the diversified land-use types and urban-rural development types, it results in the significant difference in land use-related CO_2 emissions (Liu et al., 2017; Long et al., 2008).

2.2. Data sources

Thirty-eight districts and counties in Chongqing were selected as study units. Land use data was mainly derived from the Chongqing Land Use Change Survey Data (1997–2015) provided by the Chongqing Land and Resource Department. According to *Land-use Status Classification* (GB/T21010-2007), the land use types were: arable land, garden land, forest land, grassland, water-area land, construction land (comprising cities, towns, villages, mining and industry, transportation and water conservancy facilities) and unused land. Socio-economic data such as population and GDP were mainly derived from the Chongqing Statistical Yearbooks (1997–2015) published by the Chongqing Statistical Department. Nominal GDP was converted to Constant GDP by the following formula: Constant GDP = Nominal GDP × (GDP Index)/100. GDP Index would be calculated in comparable price when the value at the base year of 1978 was equal to 100. Data on energy consumption from coal, petroleum and natural gas were obtained from the Chinese Energy Statistical Yearbooks (1997–2015) published by the National Statistical Department, and the Chongqing Statistical Yearbooks (1997–2015).

2.3. Methods

2.3.1. Computation of CO_2 emissions

CO_2 emissions from land use can be divided into *direct* and *indirect* CO_2 emissions. Direct CO_2 emissions are caused during direct land use processes, with land being the object of labor. It can be subdivided into CO_2 emissions due to transition of the land management mode and that caused by replacement of ecosystems due to transition to different land use types. Indirect CO_2 emissions are man-made emissions borne by the land and mainly refer to CO_2 emissions caused by energy consumption. Arable land and construction land are carbon sources; garden land, forest land, grassland, water-area land and unused land are carbon sinks (Cheng et al., 2014; Fang et al., 2007; Sun et al., 2015).

(1) Computation of direct CO_2 emissions from land use

Direct CO_2 emissions mainly refer to CO_2 emissions from arable land, garden land, forest land, water-area land and unused land. Such CO_2 emissions can be estimated as follows:

$$E_k = \sum e_i = \sum T_i \cdot \delta_i \tag{1}$$

Where E_k represents direct CO_2 emissions, e_i is the CO_2 emissions generated under different land use modes; T_i is the area of different land use modes; and δ_i is the CO_2 emission (absorption) coefficient of different land use types. CO_2 emission (absorption) coefficients are determined by referring to previous studies and combining them with the practical situation in Chongqing, as per Table 1 (Fang et al., 2007; Sun, 2012; Sun et al., 2015).

(2) Computation of indirect CO_2 emissions from land use

CO_2 emissions from construction land are characterized using an indirect estimation method. Namely, the quantity of CO_2 generated by energy consumed in daily life. Selected energy sources are coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, natural gas and electric power. Quantities of the above energy sources consumed are converted into standard coal quantities.

$$E_t = \sum E_{ti} = \sum E_{ni} \cdot \theta_i \cdot f_i \tag{2}$$

Where E_t is CO_2 emissions from construction land; E_{ti} is CO_2 emissions generated by consumption of the ith energy source; E_{ni} is the quantity of the ith energy source consumed; [fx] is the standard coal quantity converted from the quantity of the ith energy source consumed; and f_i is the conversion coefficient of CO_2 emissions due to the consumption of the ith energy source. Conversion coefficient from energy consumed into standard coal quantity and CO_2 emission coefficients are mainly determined based on IPCC guidelines for national greenhouse gas inventories (Fang et al., 2007; Sun et al., 2015; Zhang et al., 2012). These coefficients is also referred to previous study results and combining practical situation in Chongqing, as per Table 2 (Shi et al., 2012; Sun, 2012; Zhao et al., 2013).

(3) Computation of total CO2 emissions from land use

The total CO_2 emitted by regional land use is the sum of the direct and indirect CO_2 emissions. The computational formula is as follows:

$$E = E_k + E_t \tag{3}$$

Where E is total CO_2 emissions from land use; E_k is direct CO_2 emissions, namely, CO_2 emissions from arable land, garden land, forest land, grassland, water-area land and unused land; and E_t is indirect CO_2 emissions, namely, CO_2 emission from construction land.

2.3.2. Logarithmic Mean Divisia Index (LMDI)

Index decomposition methods are widely used in the analysis on the effect of CO_2 emissions: according to the core concept applied therein, these methods decompose the target variable into combinations of several influencing factors and then calculate the contributions of each influencing factor, to determine the primary

Table 1
Reference table for CO_2 emission coefficient of land use.

Land types	Reference value	unit
Arable land	0.0422 (Shi et al., 2012; Zhang et al., 2012)	kg/(m^2.a)
Garden land	−0.073 (Zhang et al., 2012; Zhao et al., 2013)	kg/(m^2.a)
Forest land	−0.0578 (Shi et al., 2012)	kg/(m^2.a)
Grassland	−0.0021 (Shi et al., 2012)	kg/(m^2.a)
Water-area land	−0.0252 (Lai et al., 2016; Shi et al., 2012)	kg/(m^2.a)
Unused land	−0.0005 (Shi et al., 2012)	kg/(m^2.a)

Table 2
Standard coal coefficient by energy conversion and CO_2 emission coefficient.

Energy types	Coal	Coke	Crude oil	Gasoline	Kerosene	Diesel	Fuel oil	Natural gas	Electric power
Standard coal coefficient /(kg/kg)	0.7143	0.9714	1.4286	1.4714	1.4714	1.4571	1.4286	1.2143	0.404
CO_2 emission coefficient /(t/t)	0.7559	0.855	0.5857	0.5538	0.5714	0.5921	0.6185	0.4483	0.7935

factor (Ang, 2004; Liu et al., 2007; Wang et al., 2005). The logarithmic mean Divisia index (LMDI) method is more suitable for decomposition and analysis of influencing factors of problems in the energy arena. The method has been extensively applied in the decomposition and analysis of the effect of CO_2 emissions and its influencing factors (Deng et al., 2014; Zhang and Ang, 2001). Among all land use types, construction land and cultivated land are the main CO_2 sources, and forest land is the main CO_2 sink. Especially, construction land is the space carrier of energy activities, industrial production and human living. Thus, CO_2 emissions from human economic activities are mainly concentrated on construction land such as land for mining and industry, residential land and transportation land (Li et al., 2019). It leads to that CO_2 emissions from land use are closely related to population, economy and energy factors. In this research, the LMDI method was thus used to decompose the factors influencing CO_2 emissions from land use in Chongqing, China from four aspects: effects of population scale, economic development, energy consumption (EC), and energy mix (EM).

1) Effect of population scale: the socio-economic activities of human beings are the primary influencing factors leading to increasing CO_2 emissions. Population scale is positively correlated with CO_2 emissions.
2) Economic development: with the constant growth of *per capita* gross domestic product (GDP), residents' power of consumption is also enhanced. The growing demand for energy-consuming goods such as household appliances and vehicles results in increasing CO_2 emissions. Meanwhile, policies advocating CO_2 emission reduction are also formulated as residents enhance their environmental awareness. The constant improvement of clean energy technologies allows residents to choose a sustainable living style that supports energy conservation and environmental protection, so as to reduce CO_2 emissions.
3) Energy consumption (EC): energy consumptions per unit GDP can reflect the condition of the macro-economy and the advanced energy technology progress. Poor macroeconomic performance or advanced energy technology progress can affect CO_2 emissions.
4) Energy mix (EM): EM is an effective index for measuring the energy mix (including coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, natural gas and electric power) and shows a similar trend to that of CO_2 emissions.

The calculation is expressed as follows:

$$C = P \times (G/P) \times (E/G) \times (C/E) \tag{4}$$

Where C, P, G, and E refer to the total CO_2 emissions, the total population (total number of permanent residents), regional GDP, and total energy consumption, respectively. Moreover, G/P represents *per capita* GDP, reflecting economic development, E/G denotes energy consumption per unit GDP, reflecting energy consumption intensity, and C/E reflects the EM.

Thereafter, the variation in CO_2 emissions, total population, *per capita* GDP, EC, and EM from the initial year to the *i*th year were separately recorded as ΔC, ΔC_P, ΔC_{PG}, and ΔC_{EC} , respectively. According to the LMDI method, the decomposition formula can be expressed as follows:

$$\Delta C = \Delta C_P + \Delta C_{PG} + \Delta C_{EC} + \Delta C_{EM} \tag{5}$$

Where $\Delta C_P = \nu \ln \frac{P_i}{P_0}$, $\Delta C_{PG} = \nu \ln \frac{PG_i}{PG_0}$, $\Delta C_{EC} = \nu \ln \frac{EC_i}{EC_0}$, $\Delta C_{EM} = \nu \ln \frac{EM_i}{EM_0}$, and $\nu = \frac{C_i - C_0}{\ln C_i - \ln C_0}$. Moreover, PG refers to *per capita* GDP.

From the perspective of regional CO_2 emission, Chongqing was divided into 9 regions according to the carrying capacity of regional resources-environment and economic-social development in urban-rural areas: Urban core area (*UCA*), Urban development area (*UDA*), Urban eastern new development area (*UENDA*), Urban southern new development area (*USNDA*), Urban western new development area (*UWNDA*), Northeastern touristic area (*NETA*), Northeastern typical industrial area (*NETIA*), Northeastern agricultural production area (*NEAPA*), and Southeastern ecological protection and development area (*SEEPDA*). Based on the LMDI method, this study analyzed the related factors of CO_2 emissions from land use in 9 regions of Chongqing.

2.3.3. *Geographic detector analysis*

The land use-related CO_2 emissions are a spatial differentiation feature and are mainly influenced by factors such as population, industry, economy, energy sources and land, so a geographic detector is used to discuss the main influencing factors (Liu and Yang, 2012; Ju et al., 2016; Ren et al., 2014; Wang and Xu, 2017). Influence X of variable Y is analyzed so as to explain spatial differentiation to some degree. The detection model is as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} = 1 - \frac{SSW}{SST}, \qquad SSW = \sum_{h=1}^{L} N_h \sigma_h^2 \qquad SST = N\sigma^2 \tag{6}$$

Where q is the measurement index of the influence factor; $h = 1, \ldots, L$ is the hierarchy of variable Y or factor X, namely, classification or partitioning; N_h and N are numbers of units in hierarchy h and the whole region respectively; and σ_h^2 and σ^2 are the variances of the Y values at hierarchy h and the whole region, respectively. Variables SSW and SST are the sums of the intralayer variances and the total variance of the whole region, respectively. Value of q range from [0, 1], and the greater the value, the more obvious the spatial differentiation of Y. Eight influencing factors: total population, *per capita* GDP, proportions of secondary and tertiary industries, urbanization rate, proportion of total volume of foreign trades, proportion of construction land, total energy consumed and proportion of forest land, were selected for this study, and their influences on land use-related CO_2 emissions are investigated.

3. Results and discussion

3.1. *Spatial variation and influencing factor of land use-related CO_2 emissions in regional scale*

3.1.1. *Spatial characteristics of CO_2 emissions in regional scale*

The period from 1997 to 2015 was divided into four time horizons (1997–2000, 2000 to 2005, 2005 to 2010, and 2010 to 2015). The division is mainly based on the different stages of economic development and regional development strategy. The first stage from 1997 to 2000 is that Chongqing has just become a municipality directly under the central government in China. The second stage from 2000 to 2005 is the development stage to improve the regional economic level in Chongqing. The third stage from 2005 to 2010 is the stage of regional coordinated development in Chongqing. The fourth stage from 2010 to 2015 is that Chongqing becomes the key area of China's inland opening. Table 3 shows the changes of relevant indicators of regional CO_2 emissions in Chongqing from 1997 to 2015. Based on 9 partitioned areas in Chongqing, the regional difference, evolution characteristics, and influencing factors of CO_2 emissions in Chongqing were analyzed (Fig. 2).

(1) Energy utilisation efficiencies in various areas greatly improved, with the largest improvement seen in downtown areas. During 1997 to 2015, the ECI in Chongqing declined from 1.06 ton/10^4 CNY to 0.17 tons/10^4 CNY, with a 84.23% increase in energy efficiency. Moreover, the energy utilisation efficiencies of *UCA* and *UDA* showed the largest improvements, being enhanced by 87.37% and 87.11%, respectively. The improvements in other regions were between 74% and 83%, which were slightly lower than the average improvement over the whole city (Fig. 2a).

(2) CO_2 emissions of different regions all greatly improved in which *SEEPDA* showed the largest increase. From 1997 to 2015, the CO_2 emissions in Chongqing increased from 1.09259×10^7 t to $2.58,526 \times 10^7$ (an increase of 137%). In various regions, *USNDA* exhibited the lowest increase (44%) while the increases in CO_2 emissions in other regions all exceeded 100%. In particular, *SEEPDA* and *NETA* showed the largest increases of 560% and 290%, respectively. With rapid socio-economic development in south-eastern Chongqing, the demand for energy increased rapidly while the increase in CO_2 emissions from developed areas within a 1-h travel time radius economic circle slowed down due to the effect of energy-conservation and emission-reduction policies (Fig. 2f).

(3) Increases in *per capita* CO_2 emissions in two-wing (suburban) areas were higher than those in downtown and surrounding-downtown areas. The *per capita* CO_2 emissions from Chongqing between 1997 and 2015 increased from 0.37 to 0.86 t *per capita* (an increase of 132%). The growth in *per capita* CO_2 emissions of various regions was higher in the

Table 3
Relevant indicators of regional CO_2 emissions in Chongqing from 1997 to 2015.

Periods	Regions	1	2	3	4	5	6	7
1997–2000	*UCA*	4.47	164.80	11.20	720.44	41.85	1.58	15,454
	UDA	0.99	431.19	29.30	414.00	24.05	0.99	9671
	UENDA	0.85	122.56	8.33	101.63	5.90	0.62	6033
	USNDA	0.60	156.72	10.65	96.67	5.62	0.47	4829
	UWNDA	0.63	332.14	22.57	195.18	11.34	0.50	4695
	NETA	0.36	12.76	0.87	16.71	0.97	0.06	2034
	NETIA	0.68	94.12	6.40	86.27	5.01	0.21	2835
	NEAPA	0.54	120.01	8.16	49.81	2.89	0.34	2650
	SEEPDA	0.50	37.13	2.52	40.73	2.37	0.11	2456
	CHONGQING	1.13	1471.43	100.00	1721.44	100.00	0.48	4917
2000–2005	*UCA*	1.44	185.36	13.05	538.89	40.84	1.37	27,763
	UDA	0.33	467.19	32.89	315.08	23.88	0.91	18,513
	UENDA	0.32	108.73	7.66	71.06	5.38	0.62	12,584
	USNDA	0.27	134.57	9.47	78.25	5.93	0.46	10,198
	UWNDA	0.26	295.11	20.78	151.64	11.49	0.54	10,516
	NETA	0.19	3.59	0.25	17.25	1.31	0.02	4523
	NETIA	0.25	85.17	6.00	62.38	4.73	0.23	6702
	NEAPA	0.26	107.86	7.59	46.31	3.51	0.38	6371
	SEEPDA	0.23	32.82	2.31	38.78	2.94	0.12	5927
	CHONGQING	0.43	1420.40	100.00	1319.63	100.00	0.51	11,087
2005–2010	*UCA*	1.05	304.85	12.42	987.00	38.27	2.23	69,032
	UDA	0.24	851.16	34.68	638.49	24.75	1.40	43,555
	UENDA	0.25	210.59	8.58	163.01	6.32	1.15	36,104
	USNDA	0.22	203.20	8.28	148.71	5.77	0.72	23,479
	UWNDA	0.22	432.11	17.61	293.83	11.39	0.78	23,691
	NETA	0.16	17.68	0.72	34.32	1.33	0.09	11,148
	NETIA	0.21	126.64	5.16	155.85	6.04	0.35	20,218
	NEAPA	0.18	218.03	8.88	74.81	2.90	0.78	14,736
	SEEPDA	0.19	89.85	3.66	83.33	3.23	0.32	15,438
	CHONGQING	0.32	2454.11	100.00	2579.36	100.00	0.85	27,846
2010–2015	*UCA*	0.51	300.49	11.62	844.36	33.94	2.00	109,750
	UDA	0.12	861.95	33.34	579.39	23.29	1.26	69,339
	UENDA	0.14	223.62	8.65	169.15	6.80	1.14	63,270
	USNDA	0.12	202.59	7.84	142.88	5.74	0.68	39,329
	UWNDA	0.14	498.94	19.30	368.07	14.80	0.83	44,558
	NETA	0.09	21.53	0.83	36.23	1.46	0.12	22,479
	NETIA	0.11	149.59	5.79	153.45	6.17	0.41	36,523
	NEAPA	0.12	225.98	8.74	101.83	4.09	0.85	32,324
	SEEPDA	0.11	100.59	3.89	92.42	3.71	0.37	30,345
	CHONGQING	0.17	2585.26	100.00	2487.78	100.00	0.86	49,469

Notes: 1-Energy utilisation efficiencies/(Tons/10,000 Yuan); 2-Total CO_2 emissions/10,000 Tons; 3-Proportion of CO_2 emissions/%; 4-Energy consumption/10,000 Tons; 5-Proportion of energy consumption/%; 6-Per capita CO_2 emissions/(Tonnes/Person); 7-Per capita GDP/(Yuan/Person).

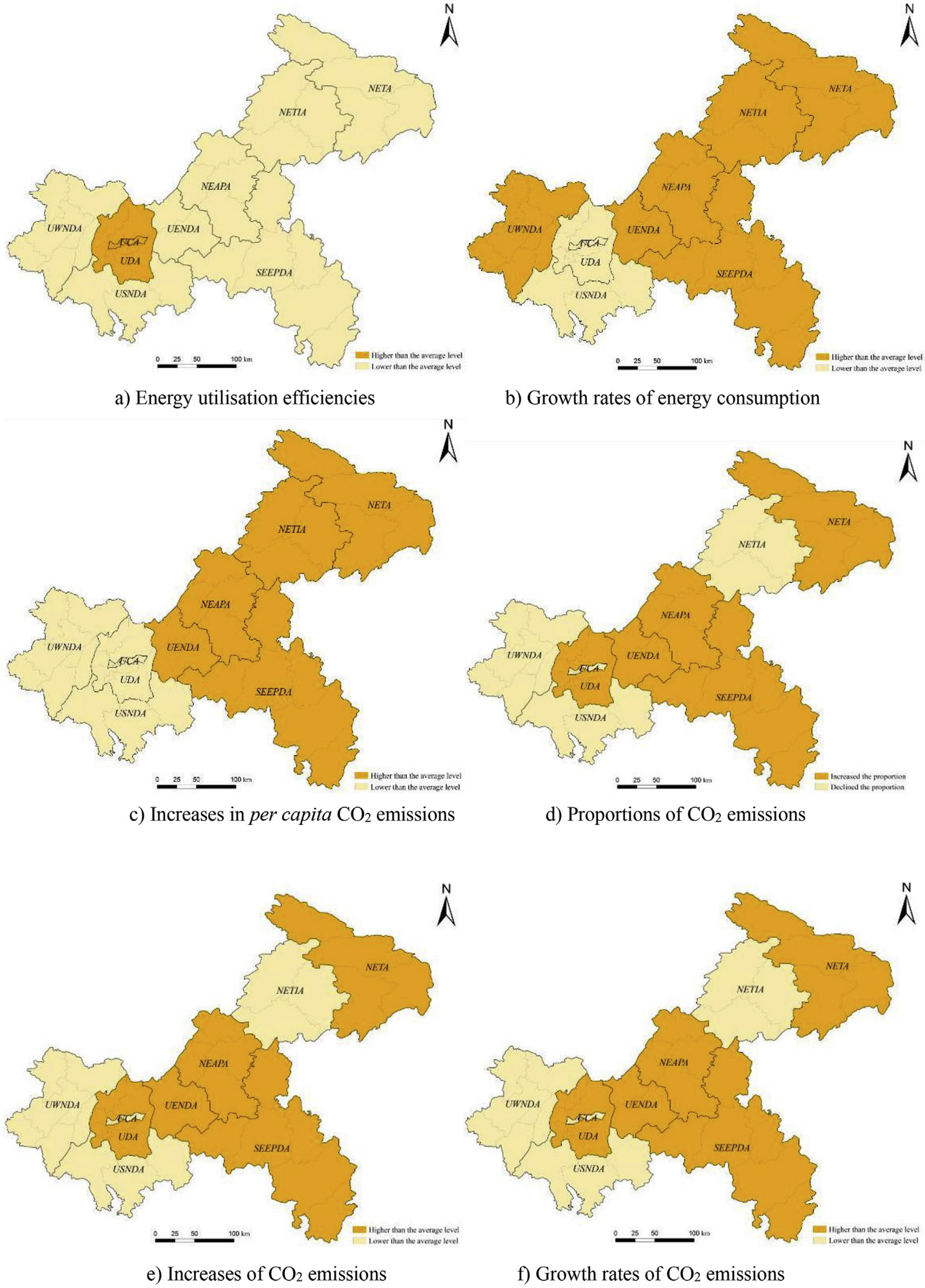

Fig. 2. Changes of regional CO_2 emission indicators in Chongqing, 1997–2015.

two-wing (suburban) areas than in downtown and surrounding-downtown areas. With rapid socio-economic development in two-wing areas, the demand for energy grows rapidly. An extensive economic development mode and a low population density cause the increase in *per capita* CO_2 emissions to be significantly higher than those in downtown and surrounding-downtown areas (Fig. 2c).

(4) The proportions of CO_2 emissions of various regions in the whole city of the total CO_2 emissions showed a significant difference and the proportions rose in a majority of regions. In various regions, the proportions of CO_2 emissions in four regions (involving *UCA*, *UWNDA*, *USNDA*, and *NETIA*) among total CO_2 emissions from the whole city declined while those from other regions increased. There was a significant internal difference in different areas, either in the 1-h economic circle or the two-wing areas, there were significant regional differences. By contrast, the proportion of CO_2 emissions in two-wing areas increased on the whole (Fig. 2d).

(5) The growth rates of energy consumption and CO_2 emission both showed a significant regional difference. The energy consumption of Chongqing (1997–2015) increased to $2.48{,}778 \times 10^7$ t from $1.34{,}443 \times 10^7$ t, increasing by 1.85 times at an annualised growth rate of 3.48%. In different areas, the growth rates of energy consumptions of *UCA*, *UDA*, and *USNDA* were lower than the average rate of growth of energy consumption across the whole city. Other areas, such as *UENDA*, *SEEPDA*, and *NEAPA* showed the largest rates of growth in energy consumption (all exceeding 5%) (Fig. 2b).

3.1.2. Decomposition of factors influencing CO_2 emissions in regional scale

(1) Decomposition of influencing factors of CO_2 emission in Chongqing. Based on the LMDI method, the factors influencing CO_2 emissions in Chongqing were decomposed from four perspectives including the effects of population scale, economic development, EC, and EM. The results are displayed in Fig. 3.

1) Effect of population scale: the growth in population triggers an increased demand for energy consumption; however, based on these results, the effect of population scale in Chongqing did not significantly influence its CO_2 emissions. Compared with the fluctuating trend in CO_2 emissions, the effect of population scale exhibited little change. Influenced by related policies such as family planning and economic and social development legislation, the net outflow of population from Chongqing was large between 2000 and 2005. Since 2005, the net outflow of population has turned to a net inflow and thereafter, population has grown steadily and the increase in CO_2 emissions declined on the whole.

2) Economic development: with the rapid development of economy and society in Chongqing, *per capita* GDP constantly increases and it exerts significant influence on CO_2 emission on the whole. The CO_2 emissions during 2000–2005 did not increase while decreased with the growth in *per capita* GDP. The main reason is that Chongqing accelerated to adjust its energy mix and therefore consumption of various energy sources such as coal rapidly reduced: coal consumption decreased from $2.35{,}344 \times 10^7$ t in 2000 to $1.78{,}288 \times 10^7$ t in 2005, decreasing by 24%. Additionally, influenced by a net outflow of population, the CO_2 emission of Chongqing gradually decreased. In other stages, the *per capita* GDP showed a consistent influence on CO_2 emissions, that is, as the rate of growth of *per capita* GDP decreased, the CO_2 emissions gradually fell by an amount exceeding that in *per capita* GDP. In particular, during the 12th Five-Year Plan in China, Chongqing enhanced its intensity of adjustment of industrial and energy mixs, thus causing its industrial structure to develop, become more clustered, and emit less carbon. Moreover, the contribution of industrial output decreased from 68.6% in 2010 to 49.4% in which the CO_2 emissions exhibited the largest reduction and economic development showed a significant effect on CO_2 emissions.

3) Energy consumption (EC): EC has a significant inhibitory effect on CO_2 emissions. With the constant reduction in energy consumption per unit GDP in Chongqing, and the constant improvement in energy utilisation efficiency, CO_2 emissions have decreased. During 2000 to 2005, the labour force decreased and therefore the economy grew at a lower rate than normal. Afterwards, with unceasing improvements to the investment environment and constant enhancement of attractive forces of the economy, the size of the labour force increased once again and the economy developed rapidly. As a result, energy consumption grew and EC decreased. Next, during the 12th Five-Year Plan, Chongqing's Government expedited the adjustment of its industrial structure and implemented policy regulation (such as energy conservation and emission reduction measures that promoted socio-economic development and transformation, such that CO_2 emissions decreased.

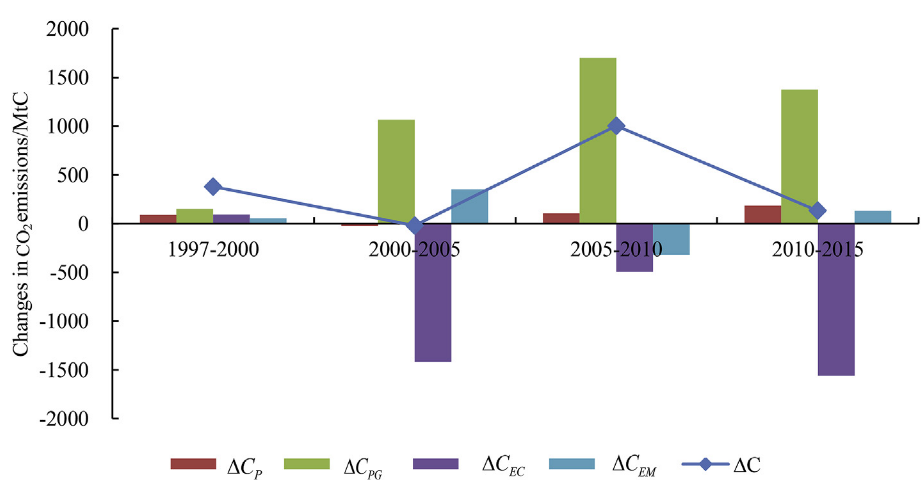

Fig. 3. Changes of CO_2 emission impact factors in Chongqing, 1997–2015.

4) Energy mix (EM): the influence of ESI on CO_2 emissions shows hysteresis, that is, the effect of energy mix adjustment shows hysteresis and the influence of energy mix adjustment in the previous stage on CO_2 emissions fails to be shown before the next stage. The proportion of consumptions of coal, oil, natural gas, and other energies in 1997 was 68.17: 13.93: 7.17: 10.73 while those in 2015 were 57.68: 14.57: 14.43: 13.32. It can be seen that the consumption proportion of coal constantly decreased while those of oil, natural gas, and other energies constantly increased; however, the energy mix did not significantly change, thus exhibiting only an insignificant influence on CO_2 emissions as a whole.

(2) Decomposition of the factors influencing CO_2 emission in various regions. According to the LMDI method, the factors influencing CO_2 emissions in the nine regions of Chongqing during 1997–2015 were decomposed. Moreover, supposing that the variation ΔC in CO_2 emissions was 1, the relative variations ΔC_P, ΔC_G, ΔC_E, and ΔC_F were calculated. They refer to the relative variations of CO_2 emissions caused by total population, *per capita* GDP, EC, and EM when CO_2 emissions change by one unit, as shown in the following Table 4.

1) Effect of population scale: During 1997 to 2000, and 2000 to 2005, the effects of population scale in various areas affected their CO_2 emissions, especially those during 2000–2005 which exerted a more significant influence. In the characteristic industrial area and the characteristic agricultural production area in the north-east of Chongqing, the effect of population scale on CO_2 emissions exhibited the greatest influence. The reason for this is that the two regions belong to the Three Gorges reservoir region and have developed later: agricultural production is considered the main economic development mode, with numerous mobile workers therein. In this case, labour force outflows result in a reduction in the population and thus a gradual decrease in CO_2 emissions. During 2005 to 2010, as this population change stabilised, the effect of population scale showed an insignificant influence on CO_2 emissions. During 2010 to 2015, the influence of changes in population on CO_2 emissions exhibited a significant regional difference, in which the effect of population in the urban development area showed the largest influence on CO_2 emission: this is because the region, as the main economic driver for the city, witnessed the inflow may people under the combined influences of various factors including housing prices and transportation link availability, resulting in the growth of CO_2 emission. The effect of population changes in the new southern development area has an inhibition effect on CO_2 emissions because of an acceleration in the rate of adjustment of its industrial structure and development of new types of industries: as a result, the CO_2 emissions declined.

2) Economic development; *per capita* GDP of different regions in Chongqing had a positive influence on CO_2 emissions. From 1997 to 2000, an insignificant difference appeared in the influences of *per capita* GDP across different regions on CO_2 emissions. During 2000 to 2005, *per capita* GDPs of new development areas in the west, east, and south, and three areas in the north-east of Chongqing inhibited overall CO_2 emissions. The growth in *per capita* GDP did not result in increased CO_2 emissions. Owing to the north-east of Chongqing having a

Table 4
Decomposition results of regional CO_2 emission factors in Chongqing, 1997–2015.

Regional name	1997–2000				2000–2005				2005–2010				2010–2015			
	ΔC_P	ΔC_{PG}	ΔC_{EC}	ΔC_{EM}	ΔC_P	ΔC_{PG}	ΔC_{EC}	ΔC_{EM}	ΔC_P	ΔC_{PG}	ΔC_{EC}	ΔC_{EM}	ΔC_P	ΔC_{PG}	ΔC_{EC}	ΔC_{EM}
UCA	0.057	0.535	0.383	0.025	2.188	4.984	−9.642	3.47	0.029	1.831	−3.74	−1.257	−6.352	−32.162	49.342	−9.827
UDA	0.459	0.239	0.126	0.176	2.035	8.098	−13.537	4.405	0.293	1.426	−5.784	−1.892	9.332	36.922	−53.966	8.713
UWNDA	0.052	0.659	0.453	−0.164	1.592	−6.823	7.366	−1.136	0.013	2.13	1.509	2.719	0.591	4.393	−3.417	−0.567
USNDA	0.868	−0.846	−0.461	1.439	0.892	−4.905	5.4	−0.388	−0.059	2.023	1.257	1.729	−17.415	−173.144	203.97	−12.411
UENDA	0.032	0.696	0.305	−0.033	0.993	−6.14	8.136	−1.989	0.06	1.595	2.936	1.886	1.126	9.346	−9.855	0.383
SEEPDA	0.034	0.193	0.104	0.669	−2.021	11.255	−9.965	1.731	−0.003	1.189	−4.163	1.111	−0.275	5.989	−5.25	0.536
NEAPA	0.146	0.648	0.361	−0.041	18.525	−75.69	64.151	−5.986	−0.27	2.719	36.051	15.799	−0.328	4.717	−2.845	−0.545
NETIA	0.259	0.434	0.344	0.126	16.241	−75.534	88.456	−28.163	−0.056	1.814	22.46	35.22	0.294	16.528	−18.684	2.863
NETA	0.011	0.071	−0.119	1.038	0.27	−1.513	1.198	1.045	−0.037	1.056	0.447	−0.408	−0.391	3.556	−3.151	0.986
Chongqing	0.235	0.398	0.243	0.144	1.134	−50.545	67.115	−16.703	0.104	1.695	23.405	15.09	1.398	10.493	−11.892	1.001

fragile ecological environment, mainly encompassing areas of developing agriculture and tourism services, CO_2 emissions increased slowly. During 2005 to 2010, socio-economic development of the whole city increased rapidly: in this context, *per capita* GDP greatly influenced CO_2 emissions and an insignificant difference was shown in the influences of *per capita* GDPs of various regions on CO_2 emissions. After undergoing rapid development during the 11th Five-Year Plan, a great difference was shown in the influence of *per capita* GDP in various regions on CO_2 emissions, showing a significant regional difference in terms of the influence thereon. The *per capita* GDPs in the urban core area and the new southern development area both exhibited an inhibitory effect on CO_2 emissions. By contrast, the *per capita* GDP in other areas promoted their CO_2 emissions. The influence of *per capita* GDP in the urban development area and the north-eastern industrial area on CO_2 emissions was the most significant. Under the effect of socio-economic development and transformation, the urban core area mainly developed commercial and financial service industries, with a high economic output value and a low CO_2 emissions footprint. The characteristic industrial area in the northeast of Chongqing accelerated industrial development, which had a high demand for energies, and thus CO_2 emissions greatly increased. Other regions accelerated their industrial transformation and upgrading and their energy demands increased, which significantly influenced the CO_2 emissions.

3) Energy consumption (EC): the inhibitory effects of ECs in various areas in Chongqing on CO_2 emissions fluctuated while generally strengthening. During 1997 to 2000, except for the new development area in the south and touristic area in the north-east of Chongqing, the ECs of other areas failed to inhibit CO_2 emissions (albeit to little effect overall). During 2000 to 2005, the ECs in the urban core area, the urban development area, and the three areas in the south-east of Chongqing exhibited a significant inhibitory effect on CO_2 emissions. As for other areas, the ECs of the characteristic agricultural production, and industrial, areas in the north-east of Chongqing exerted a significant influence on CO_2 emissions, with a high energy consumption per unit GDP arising as a result. During 2005 to 2015, the inhibitory effects of ECs in various areas on CO_2 emissions fluctuated in which the new development area in the south of Chongqing, and the urban core area, showed the largest change. The ECs in these two areas failed to inhibit CO_2 emissions, both showing a poor energy-conservation and emissions-reduction effect. In the other areas, as some policies (including energy conservation and emission reduction and adjustment of industrial structure) were implemented, energy consumption per unit GDP declined and therefore CO_2 emissions were inhibited.
4) Energy mix (EM): the influences of energy mix on CO_2 emissions from various areas in Chongqing fluctuated. During 1997 to 2005, the influences of EMs of the urban development area and the urban core area on CO_2 emissions were strengthened. The energy mix of the western, southern, and new eastern development areas, as well as that in the industrial and agricultural production districts in the north-east of Chongqing exhibited an inhibitory effect on CO_2 emissions. The influence of the adjustment of energy mix on CO_2 emissions was relatively significant: during 2005–2015, EMs of the urban development area and the north-eastern touristic area both exhibited significant influences on CO_2 emissions. Except for this, the influences of EMs of the other areas on CO_2 emissions all declined. In particular, the agricultural production and industrial areas in the north-east of Chongqing showed more significant changes in terms of the influence of EM on CO_2 emissions. In these two areas, economic development and transformation promoted industrial development and transformation, which constantly optimised the regional energy consumption structure to thus reduce CO_2 emissions; however, where the energy consumption structure was dominated by coal the influence of energy mix on CO_2 emissions was weakened to some extent.

3.2. Spatial variation and influencing factor of land use-related CO_2 emissions in county scale

3.2.1. Spatial characteristics of CO_2 emissions in county scale

Landforms in Chongqing are diversified, with different levels of socio-economic development in urban and rural areas. This results in obvious differences in land use-related CO_2 emissions between different districts and counties. For the convenience of a comparative analysis, a standard treatment was implemented for land use-related CO_2 emissions in different districts and counties in different years. CO_2 emissions were divided into four levels: heavy (0.75–1.00), moderate (0.50–0.75), mild (0.25–0.50) and slight (0–0.25). The spatial analysis function in ArcGIS 9.3 software was used for description, and the results are shown in Fig. 4. There were quite significant spatial differences in the land use-related CO_2 emissions of different districts and counties during different periods.

(1) Districts and counties with heavy emissions were mainly concentrated in core areas of the major city of Chongqing. Here, CO_2 emissions increased from 2,904,700 t in 1997 to 5,747,900 t in 2015 which, respectively, comprised 26.59% and 22.23% of total land use-related CO_2 emissions of the whole city in the those years. Districts with heavy CO_2 emissions in 1997 were Yuzhong, Jiulongpo, Jiangjin and Hechuan, while those in 2000 were Yuzhong, Jiulongpo and Shapingba. Those in 2005 were Yuzhong and Jiulongpo, those in 2010 were Yuzhong, Jiulongpo, Yubei and Wanzhou, and those in 2015 were Yuzhong, Jiulongpo and Yubei. Chongqing is an old industrial base, and its industrial development is concentrated in core urban development areas such as Yuzhong and Jiulongpo Districts. Since Chongqing became a municipality administered by the central government, the land use-related CO_2 emissions in these two districts have been increasing. With the "retreat into three" of the industrial structure adjustment in the main urban area, industry has gradually moved towards the peripheral areas of the old city. Yubei District-represented urban development extension region undertook industrial transfer from old city area. The region gradually extended around the main urban areas. As a central city in the Three Gorges Reservoir Region in northeast Chongqing, Wanzhou District had high urbanization and industrialization levels, so its land use-related CO_2 emissions were relatively high and were considered 'heavy' in 2010.
(2) Districts and counties with moderate emissions were mainly concentrated in major city expansion areas, regions around main urban areas, and regional hub cities. CO_2 emissions increased from 2,945,200 t in 1997 to 6,714,200 t in 2015, which comprises 26.96% and 25.97% of the total land use-related CO_2 emissions for the whole city, respectively, in

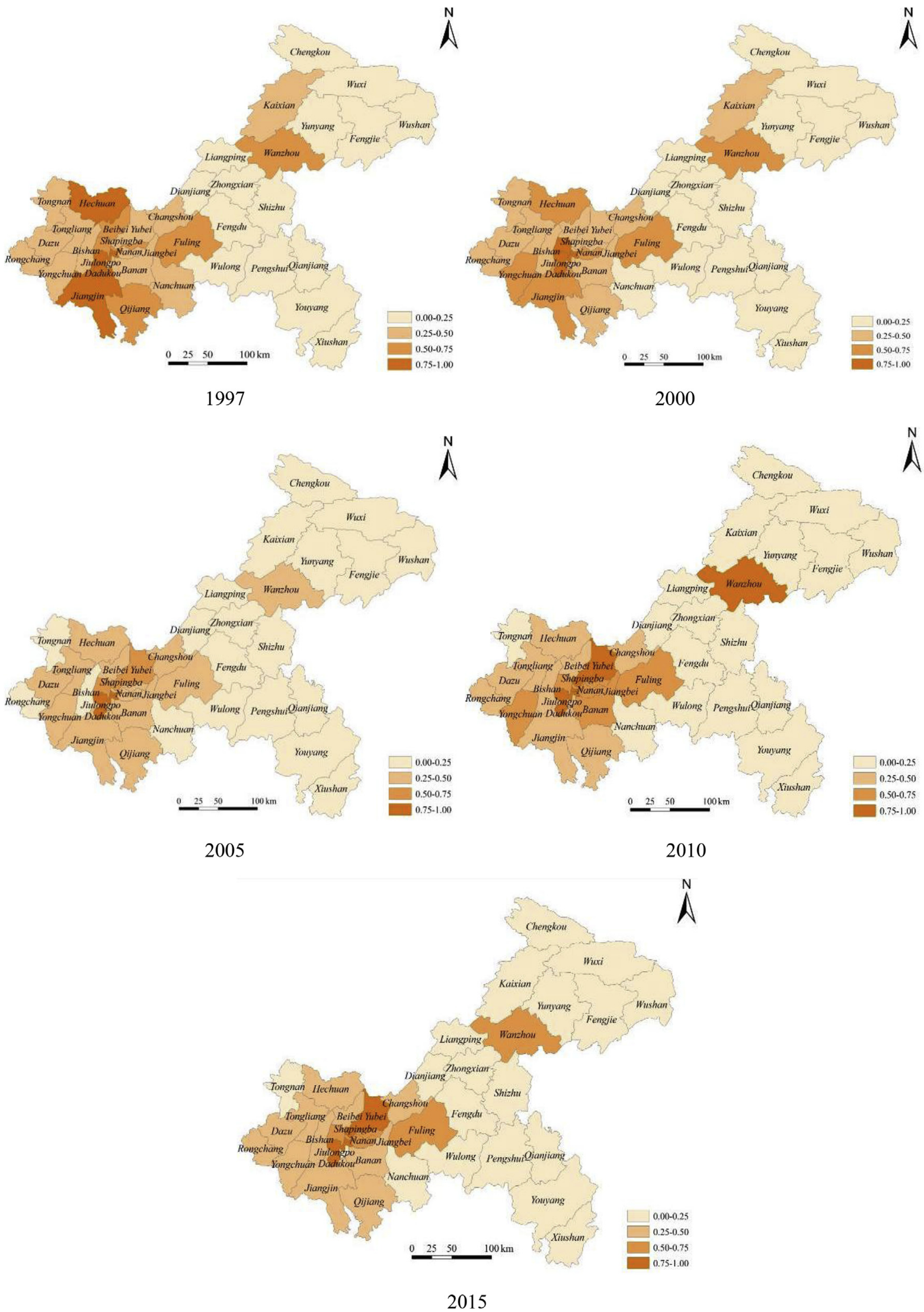

Fig. 4. Spatial-temporal changes of land use-related CO_2 emissions in Chongqing, 1997–2015.

those years. During the nearly 20 years from 1997 to 2015, urban-rural socioeconomic development in Chongqing was rapid, and its regional economic development expanded from the center to the periphery. Since coming under the direct control of the central government, developed areas have expanded from the old city areas of Yuzhong and

Jiangbei Districts to major urban areas including Yubei, Dadukou, Shapingba, Jiulongpo, Nan'an, Ba'nan and Beibei Districts until Qijiang District, Jiangjin District, Hechuan District, Yongchuan District and Fuling District-represented region around the main urban areas. It can be seen from the picture that three districts—Shapingba, Fuling and Wanzhou—were basically within a moderate-emission region. These districts had relatively high socioeconomic development and large populations, and their land was used mainly for construction. The regional CO_2 emissions were relatively large, so they were within a moderate-emission region.

(3) Districts and counties with mild CO_2 emissions were mainly concentrated around major urban areas. CO_2 emissions increased from 4,044,200 t in 1997 to 8,792,600 t in 2015, representing 37.02% and 34.01% of the total land use-related CO_2 emissions of the whole city in those years. CO_2 emission in this region was the region with the largest proportion of CO_2 emission from land use in the whole city, and quantity of districts and counties was also about ten. Regions around major urban areas were the main battlefield of future economic development with integration of urbanization, industrialization and agricultural modernization. This region was a broad area with the main landforms being shallow hills and flat dams. On the one hand, this region undertook industrial transfer from main urban areas in Chongqing with certain CO_2 emission. On the other hand, this region was also the main agricultural development region in Chongqing with a large proportion of arable land accompanied by certain amount of CO_2 emissions. So, this region was within a mild-emission region and its land use-related CO_2 emissions were generally increasing. For example, districts like Tongnan, Tongliang, Dazu, Rongchang, Bishan and Changshou District were basically within a mild-emission region, mainly because of its gradually increasing industrialization level and relatively high agricultural modernization level.

(4) Districts and counties with low emissions were mainly concentrated in the Wuling mountainous area in southeast Chongqing and the Three Gorges Reservoir Area in northeast Chongqing. CO_2 emissions increased from 1,031,800 t in 1997 to 4,598,000 t in 2015 comprising 9.44% and 17.79% of total land use-related CO_2 emissions of the city in those years. Land use-related CO_2 emissions in this region were the lowest of the whole city, but the quantity of districts and counties kept above 15. The Wuling mountainous area in southeast Chongqing and the Three Gorges Reservoir area in northeast Chongqing are ecological conservation areas. The main landforms are low hills and mountains, and the land use types are mainly arable land and water areas. The forest coverage rate was high and CO_2 emissions from land use were small. Some counties like Youyang, Wuxi and Chengkou County exerted a carbon fixation effect. Since Chongqing became a municipality administered by the central government, this region enjoyed a certain degree of urban-rural socioeconomic development that somewhat increased the total regional CO_2 emissions. However, on the whole, this region persisted in the idea "development at points and protection on surfaces", so the ecological environment still had a good status. Districts and counties like Qianjiang District, and Wulong, Shizhu, Xiushan, Youyang, Pengshui, Liangping, Chengkou, Fengdu, Dianjiang, Zhong, Yunyang, Fengjie, Wushan and Wuxi Counties, were always within low-emission regions. The number of districts and counties increased from 15 in 1997 to 19 in 2015.

3.2.2. Causal analysis of factors influencing CO_2 emissions in county scale

As land use-related CO_2 emissions are influenced by multiple factors, eight indexes reflecting population size, economic development, industrial structure, energy consumption and land structure, respectively, were selected. The main influences on the spatial layout of land use-related CO_2 emissions were investigated. First of all, coupling and matching analysis was carried out using CO_2 emission grading from land use in districts as well as counties and cluster grading of influence factors. CO_2 emissions grading and cluster grading and matching was performed in ArcGIS (Fig. 5). According to the geographic detector model, natural cluster grading and partitioning were conducted for the influencing factors. The degrees of influence of these factors on land use-related CO_2 emissions in districts and counties were computed using Formula (7). The influencing factors were total population (0.63), *per capita* GDP (0.76), proportion of secondary and tertiary industries (0.63), urbanization rate (0.70), proportion of total volume of foreign trades (0.56), proportion of construction land (0.63), total energy consumed (0.96) and proportion of forest land (0.49). Thus, it can be seen that land use-related CO_2 emissions in county regions of Chongqing were mainly influenced by factors such as total energy consumed, *per capita* GDP and urbanization rate, followed by total population, proportion of secondary and tertiary industries, proportion of construction land, etc.

(1) Areas with heavy CO_2 emissions from land use in Chongqing were mainly concentrated in the core areas of the main city. As an old industrial base in China, Chongqing has a favorable industrial development base and conditions, with its original economic development mainly centering on core areas of the main city. These areas enjoy the most developed economy in Chongqing and have high urbanization and industrialization levels, the strongest population bearing capacity, the largest proportion of construction land and the highest total energy consumed, so these areas also have the highest land use-related CO_2 emissions.

(2) Areas with moderate land use-related CO_2 emissions were mainly concentrated in the main urban extension region, regions around main urban area, and regional hub cities. Influenced by economic radiation and industrial migration as well as the main landforms of the region (shallow hills and flat dams), these areas have developed economies, high urbanization levels and rapid development of new types of industry. Meanwhile, the populations in these districts and counties have gradually migrated into these areas. As a result, the population bearing capacity is gradually strengthened and is accompanied by rapidly growing areas of construction land and gradual increases in energy consumption. Therefore, the land use-related CO_2 emissions in these areas are also gradually being reinforced.

(3) Areas with mild and low land use-related CO_2 emissions were mainly concentrate in the Wuling mountainous area in southeast Chongqing and the Three Gorges Reservoir area in northeast Chongqing. Influenced by topographical factors, these areas are mainly hilly and mountainous. The proportion of forest land is large, and the carbon fixation capability is strong. Under the guidance of environmental protection and ecological construction strategies, economic development in these areas is relatively low, with a slow transfer of the agricultural labor force and slow development of secondary and tertiary industries. Moreover, the urbanization level is relatively low, as are the industrialization level, population density and proportion of construction land.

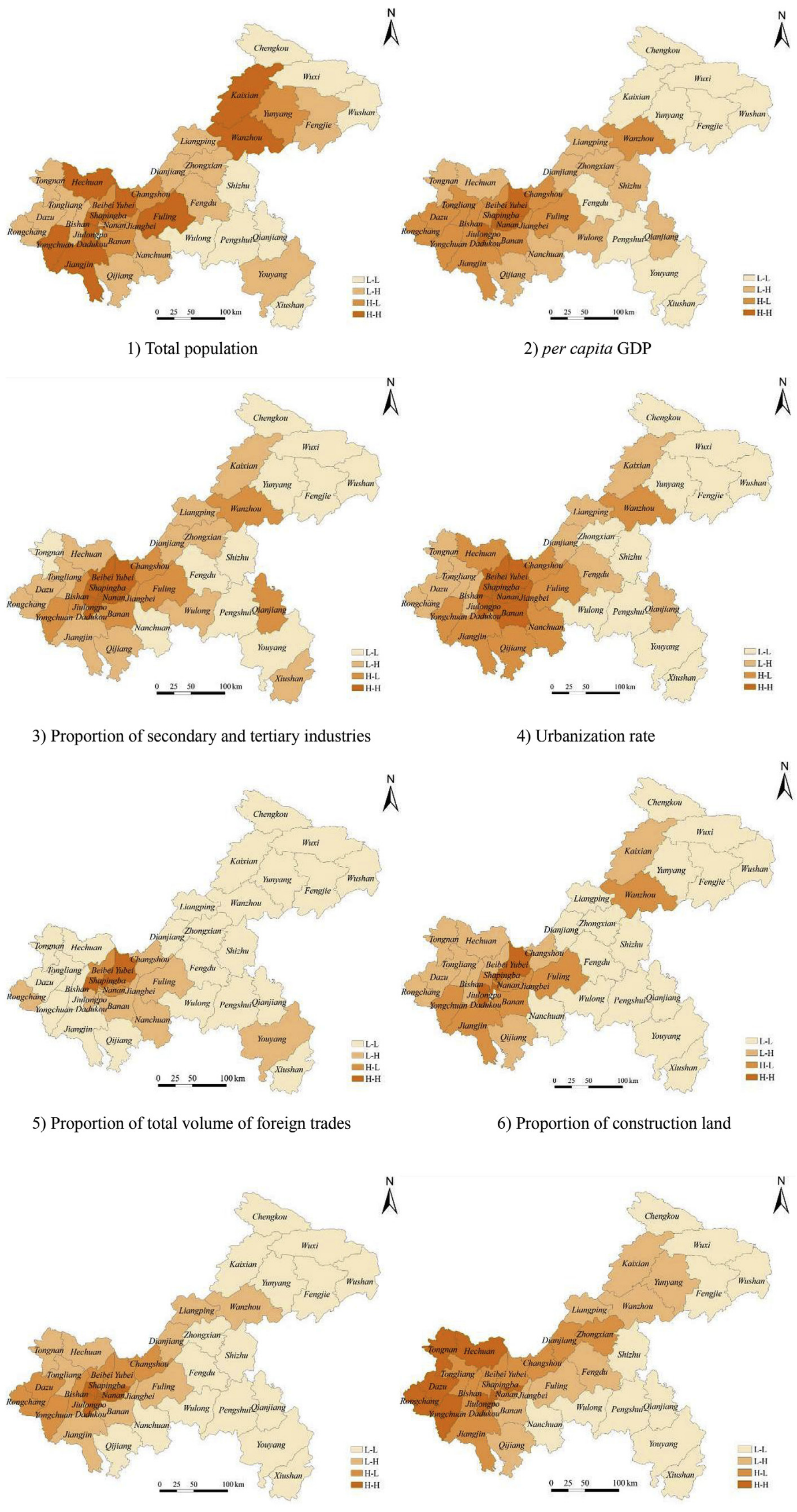

Fig. 5. Spatial matching distribution of land use-related CO_2 emissions and influencing factors of Chongqing in 2015.

Energy consumption is the lowest, so these areas have the lowest land use-related CO_2 emissions.

3.3. Problem discussion and policy enlightenment

(1) Estimates of CO_2 emissions from regional land use were mainly based on land use data and energy consumption data. Hence, improving the accuracy of land use and energy consumption data was critical for implementing the study on land use-related CO_2 emissions. Existing land use data came from land use change survey data from different regions. Ways to acquire high resolution land use data using remote sensing technology needs further discussion and analysis. It is easy to acquire energy consumption data at the national and provincial levels but more difficult at the district and county levels. Moreover, a series of other problems, such as effectively relating energy consumption data to construction land, and extracting energy consumption data, remain to be studied. Direct and indirect methods were used for the estimation of land use-related CO_2 emissions. The key to this method lies in the determination of CO_2 emission coefficients. Even though consensus has been formed on the method of estimating CO_2 emissions, there is no unified standard for CO_2 emission coefficients. Empirical values are mostly used, so ways of discussing CO_2 emission coefficients according to different spatial scales and different regional spaces will be a future research focus. Observational experimental studies should be carried out on natural carbon reserves and carbon flux in different land use types in typical regions so as to acquire background and corrected values for CO_2 emission coefficients. National and regional standards relating to CO_2 emission coefficients will be gradually formed, which will lay a solid foundation for estimation of land use-related CO_2 emissions in the future.

(2) Overall, the rate of growth in CO_2 emissions from Chongqing has decreased while there remain significant regional differences therein. The urban core area has its industrial structure dominated by modern financial services, with a high population density and significant economic benefits accruing thereto. With the constant development of diverse energy-conservation industries and technologies including low-carbon industry and constant deepening of the idea of low-carbon lifestyles, CO_2 emissions have gradually decreased and then stabilised. As main areas for undertaking urbanization and industrialization of the urban core area, the urban development area and the new urban development areas are located within a 1-h economic circle. The urbanization and industrial development of these areas demands a constant increase in energy consumption, causing the CO_2 emissions to increase. Therefore, it is necessary to incorporate low-carbon ideas into various plans in the areas to plan and guide urbanization and industrial development and facilitate the transformation and upgrading of its industrial structure. Additionally, these regions need to increase their science and technology inputs, constantly improve their level of energy-conservation and emission-reduction technology, reduce energy consumption per unit GDP, enhance energy utilisation efficiency, and control the growth in their CO_2 emissions. As the major ecological barrier to the whole city, the two-wing areas exist in a fragile ecological environment and have a low resource and environmental bearing capacity. Therefore, it is improper to conduct high-intensity development and construction therein. Instead, it is suggested that government expedite industrial transformation and upgrading, change the economic development mode and promote the transformation of regional green development mode, thus reducing CO_2 emissions. This can be realised by developing tertiary industries (including ecological agriculture and tourism), taking advantage of the rich natural and ecological resources of the two-wing areas and being guided by green development ideas. Additionally, by taking some measures such as afforestation and comprehensive land-improvement, the regional ecological environment can be improved to thus increase regional vegetation coverage and improve the carbon sink capacity of regional land resources.

4. Conclusions

(1) At regional scale, the CO_2 emissions and energy consumptions of various areas in Chongqing constantly increased and significant differences were found in various areas. Moreover, the CO_2 emissions of the ecological protection and development area in the south-east, and touristic area in the north-east, of Chongqing showed the largest increase. In terms of energy consumption, the new development area in the west, the ecological protection and development area in the south-east, and agricultural production area in the north-east of Chongqing exhibited the largest growth rates. Energy utilisation efficiency improved under influences of various low-carbon policies and low-carbon development concepts. Moreover, the rate of growth of CO_2 emissions decreases and significant differences were seen in the growth rates of CO_2 emissions and increases in *per capita* CO_2 emissions in various areas: the change in two-wing (suburban) areas was faster than that in downtown, and surrounding-downtown, areas.

(2) At regional scale, the influences of various decomposed factors on the change of CO_2 emissions fluctuated: as influenced by related policies such as family planning and economic and social development, the effect of population shows an insignificant influence on CO_2 emissions. With the constant increase in *per capita* GDP, economic development greatly influences CO_2 emissions. Additionally, given that the energy consumption per unit GDP of the whole city constantly declined, ECI showed a significant inhibitory effect on CO_2 emissions while ESI exhibited significant hysteresis. A spatio-temporal difference is shown in decomposed influencing factors affecting CO_2 emissions in different areas.

(3) At county scale, influenced by complicated landform types and different levels of urban-rural socioeconomic development, heavy land use-related CO_2 emissions were mainly concentrated in the core areas of the main city; moderate CO_2 emissions occurred in main urban extension region, regions around the main urban area, and regional hub cities; and low CO_2 emissions were mainly concentrated in the Wuling mountainous area in southeast Chongqing and the Three Gorges Reservoir area in northeast Chongqing.

(4) At county scale, main factors influencing CO_2 emissions from land use in Chongqing included total energy consumed, *per capita* GDP and urbanization rate. Factors like total population, proportion of secondary and tertiary industries and proportion of construction land also influenced CO_2 emission levels from land use.

(5) The main measures of reducing CO_2 emissions are establishing low-carbon land use pattern; adjusting energy mix and industrial structure; promoting orderly population transfer; building ecological compensation and economic incentive mechanism; formulating differential land use policies. On one hand, for main urban area and the region around main urban area with high CO_2 emissions,

construction land scale should be controlled and industrial structure should be optimised in order to reduce CO_2 emissions on construction land; on the other hand, for southeast and northeast regions with low CO_2 emissions, economic growth mode should be transited to improve land intensive use level.

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