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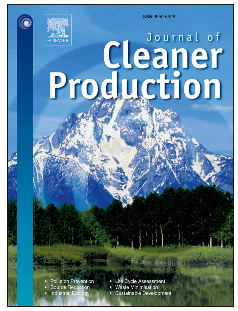

Patterns of CO_2 emissions in 18 central Chinese cities from 2000 to 2014

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Patterns of CO_2 emissions in 18 central Chinese cities from 2000 to 2014

Xinwanghao Xu[a], Hong Huo[b], Jingru Liu[a,*], Yuli Shan[c,*], Yuan Li[c,d,*], Heran Zheng[c], Dabo Guan[c], Zhiyun Ouyang[a]

[a] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, 100085 Beijing, China
[b] Institute of Energy, Environment and Economy, Tsinghua University, Beijing 100084, China
[c] Water Security Research Centre, School of International Development, University of East Anglia, Norwich NR4 7TJ, UK
[d] State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing 100084, China

*Corresponding authors: Jingru Liu (liujingru@rcees.ac.cn), Yuli Shan (Y.Shan@uea.ac.uk), Yuan Li (y.li4@uea.ac.uk)

Abstract

With the Rise of Central China Plan, the central region has had a great opportunity to develop its economy and improve its original industrial structure. However, this region is also under pressure to protect its environment, keep its development sustainable and reduce carbon emissions. Therefore, accurately estimating the temporal and spatial dynamics of CO_2 emissions and analysing the factors influencing these emissions are especially important. This paper estimates the CO_2 emissions derived from the fossil fuel combustion and industrial processes of 18 central cities in China between 2000 and 2014. The results indicate that these 18 cities, which contain an average of 6.57% of the population and 7.91% of the GDP, contribute 13% of China's total CO_2 emissions. The highest cumulative CO_2 emissions from 2000 to 2014 were from Taiyuan and Wuhan, with values of 2268.57 and 1847.59 million tons, accounting for 19.21% and 15.64% of the total among these cities, respectively. Therefore, the CO_2 emissions in the Taiyuan urban agglomeration and Wuhan urban agglomeration represented 28.53% and 20.14% of the total CO_2 emissions from the 18 cities, respectively. The three cities in the Zhongyuan urban agglomeration also accounted for a second highest proportion of emissions at 23.51%. With the proposal and implementation of the Rise of Central China Plan in 2004, the annual average growth rate of total CO_2 emissions gradually decreased and was lower in the periods from 2005 to 2010 (5.44%) and 2010 to 2014 (5.61%) compared with the rate prior to 2005 (12.23%). When the 47 socioeconomic sectors were classified into 12 categories, "power generation" contributed the most to the total cumulative CO_2 emissions at 36.51%, followed by the "non-metal and metal industry", "petroleum and chemical industry", and "mining" sectors, representing emissions proportions of 29.81%, 14.79%, and 9.62%, respectively. Coal remains the primary fuel in central China, accounting for an average of 80.59% of the total CO_2 emissions. Industrial processes also played a critical role in determining the CO_2 emissions, with an average value of 7.3%. The average CO_2 emissions per capita across the 18 cities increased from 6.14 metric tons in 2000 to 15.87 metric tons in 2014, corresponding to a 158.69% expansion. However, the average CO_2 emission intensity decreased from 0.8 metric tons/1,000 Yuan in 2000 to 0.52 metric tons/1,000 Yuan in 2014 with some fluctuations. The changes in and industry contributions of carbon emissions were

city specific, and the effects of population and economic development on CO_2 emissions varied. Therefore, long-term climate change mitigation strategies should be adjusted for each city.

Keywords: CO_2 emissions, central Chinese cities, emission intensity, per capita emissions

1. Introduction

Despite slowing economic activity and changing economic structure, China has remained the world's largest energy consumer and accounts for 23% of global energy consumption (BP, 2016). Nearly three-quarters of the growth in global carbon emissions from the burning of fossil fuels and cement production between 2010 and 2012 occurred in China (Liu et al., 2015c). In 2013, China released 25% of the total global CO_2, 1.5 times that released by the United States (Liu et al., 2015b; Mi et al., 2017). As China is the largest global source of CO_2 emissions, China's emissions need to be accurately quantified and well understood (Liu et al., 2013; Wang et al., 2012; Wang and Cai, 2017), and China should prioritize climate change mitigation. In its 2015 Intended Nationally Determined Contributions, China promised to decrease its CO_2 emissions per unit of gross domestic product (GDP) by 60-65% (based on 2005 levels) by 2030 (xinhua, 2015). However, in order to achieve China's national mitigation targets, sub-administrative regions, such as cities, should be assigned responsibilities accordingly.

Cities are the centres of wealth and creativity, and with their high population densities and economies, they are being recognized as major components in the implementation of climate change adaption and CO_2 emission mitigation policies (Chavez and Ramaswami, 2014; Hoornweg et al., 2011; Kennedy et al., 2012; Kennedy et al., 2010; Wang et al., 2012). The inventory of CO_2 emissions listed by the energy consumption of individual cities is a quantitative emissions accounting method that allows for the visualization of change trends and serves as the basis for analysing the potential to reduce emissions (Bi et al., 2011). Therefore, understanding the emission status of individual cities is a fundamental step for proposing mitigation actions (Hoornweg et al., 2011). Although numerous studies have been carried out to investigate CO_2 emissions at the community (Song et al., 2012), town (Feng et al., 2015), city (Cai and Zhang, 2014; Guo et al., 2012; Hillman and Ramaswami, 2010; Liu et al., 2012b; Shao et al., 2016b; Wang et al., 2012; Yu et al., 2012), provincial (Bai et al., 2014; Geng et al., 2011b; Liu et al., 2012a; Zhang et al., 2017a), region (He et al., 2017), and national levels (Guan et al., 2008; Liu et al., 2015c), the CO_2 emission inventories of Chinese cities have not been well documented when compared with the global research. This knowledge gap is due to the various definitions of city boundaries, the limited quality of the emission activity data, and non-unified research methods, which together make it difficult to estimate city-scale carbon emissions (Kennedy et al., 2010; Liu et al., 2015b; Wang and Cai, 2017). Complete energy balance tables and CO_2 emission inventories are available for Chinese megacities (Beijing, Tianjin, Shanghai, and Chongqing) (Geng et al., 2011b) and a few provincial capital cities (Shan et al., 2017). However, another 250+ cities of various sizes and developmental stages lack consistent and systematic energy statistics, and the accuracy of the existing data is not absolutely guaranteed (Liu et al., 2015c). Moreover, CO_2 emissions are calculated as the product of activity data and an appropriate emission factor (Sugar et al., 2012). Most previous studies have employed the emission factor recommended by the IPCC, which might not be suitable for China's situation (Liu et al., 2015c). To accurately estimate CO_2 emissions, Liu et al. (2015c) utilized updated emissions factors that better accord with the situation in China to re-calculate the CO_2 emissions. These authors found that the revised estimate for CO_2 emissions derived from fossil fuel and cement consumption was 2.49 GtC in 2013, 12%-14% less than that estimated by the UNFCCC and EDGAR. Some studies have examined CO_2 emissions from a sectoral perspective, such as household carbon emissions (Allinson et al., 2016; Zhang et al., 2017b), commercial sector (Wang and Lin, 2017) and industrial processes (Liu et al., 2014), which would also provide a basis for estimating carbon emissions for cities.

Generally, carbon accounting can be defined as having 3 scopes: (1) all direct CO_2 emissions occurring within the city; (2) indirect CO_2 emissions related to purchased electricity and steam and heating consumption; and (3) other life-cycle emissions excluded from scopes 1 and 2 (Chavez and Ramaswami, 2014; Liu et al., 2015a). Due to China's large size and imbalanced levels of development, the lifestyles, resource endowments and levels of economic development in different provinces and cities are significantly different (Feng et al., 2012; Guan et al., 2017; Liu et al., 2012a; Wu et al., 2017; Yu et al., 2012). Consequently, a single mitigation action will not be suitable for all of China's 30 provinces and autonomous regions (Liu et al., 2015b). In addition, CO_2 emission mitigation policies should by adjusted according to the needs of the different cities. In recent years, some cities have established CO_2 emission inventories, which can help the government advance and implement mitigation plans and propose pragmatic and effective measures and schemes to reduce CO_2 emissions (Geng et al., 2011a). Based on the considerations above, the newly constructed emission inventories are compiled using the definition provided by the IPCC territorial emission accounting approach and cover 47 socioeconomic sectors, 20 energy types and 7 primary industry products, which in turn correspond to the national and provincial inventories (Shan et al., 2017).

China's level of industrialization and urbanization has become remarkable since joining the WTO in 2001 (Liu et al., 2012a). The nation's economy in 2014 was almost 4 times the size of that in 2000 (Shan et al., 2016c). China's total energy consumption has also increased dramatically from 1470 million metric tons coal equivalent (tce) in 2000 to 4260 million tce in 2014 (Shan et al., 2017). The adoption of the Rise of Central China Plan in 2004 offered a great opportunity for the central cities to develop. The central region has also borne a significant responsibility as the linkage between the eastern and western regions during the industrial structure transition. Additionally, the central region is considered to be the production base of agriculture, energy and raw materials, especially as the development in Shanxi and Henan has relied heavily on coal. Due to imbalances in levels of economic development and resource distributions, the regional characteristics of energy consumption in China also display distinct patterns (Li et al., 2016). As such, local policymakers and researchers should work to understand the spatial and temporal characteristics of CO_2 emissions and the methods that central China employs to avoid developing its economy at the expense of the environment. Consequently, this study aims to estimate the CO_2 emissions of 18 central Chinese cities within six urban agglomerations from 2000 to 2014. Moreover, we analyse and compare the characteristics of CO_2 emissions and examine similarities and differences in CO_2 emissions in those cities and the cities located in the other regions of China and abroad. The methodologies used in this study are presented in section 2, where we give a general overview of the construction of the CO_2 emission inventory, data sources, and research objectives. In section 3, we describe the temporal and spatial variations of CO_2 emissions and analyse the contributions of various sectors and energy types. In this section, emissions intensity and per capita emissions are also introduced to illustrate the relationships between energy consumption, economic development and population expansion. Finally, in section 4, we summarize our principal findings and present practical measures to mitigate CO_2 emissions.

2. Methodology

2.1. Case choice

In this study, we selected 18 cities from 6 central provinces (including Shanxi, Henan, Anhui, Hubei, Hunan, and Jiangxi) and compiled a CO_2 emissions inventory for the period from 2000 to 2014. These 18 cities are affiliated with the Taiyuan Urban Agglomeration (TYUA), Zhongyuan Urban Agglomeration (ZYUA), Wanjiang Urban Belt (WJUB), Greater Changsha Metropolitan Region (GCMR), Wuhan Urban Agglomeration (WHUA), and City Cluster surrounding Poyang Lake (CCPL) (NDRC, 2010) (Fig. 1). In addition, basic information about these cities is included in Table 1.

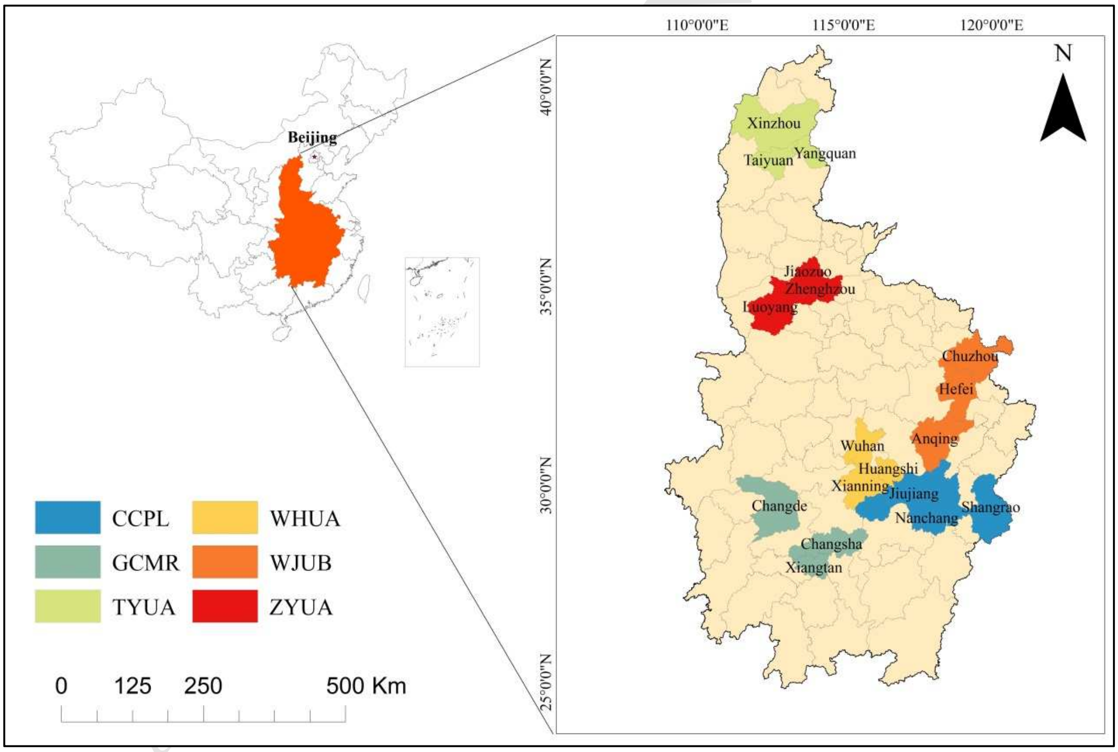

Fig. 1 The 18 central Chinese cities within six urban agglomerations in central China

Note: TYUA: Taiyuan urban agglomeration; ZYUA: Zhongyuan urban agglomeration; WJUB: Wanjiang Urban Belt; GCMR: Greater Changsha Metropolitan Region; WHUA: Wuhan urban agglomeration; CCPL: City Cluster surrounding Poyang Lake (The same below).

Table 1 The socio-economic characteristics of 18 central Chinese cities in 2014

Regions	cities	GDP (10^8 Yuan)	Area (km^2)	Population (10^4 persons)	GDP per capita (Yuan/capita)	Population density ($persons/km^2$)
TYUA	Taiyuan	2531.09	6988	369.7425	68455	529
	Xinzhou	680.30	25152	312.8460	21746	124
	Yangquan	616.62	4570	139.2674	44276	305
ZYUA	Zhengzhou	6776.99	7446	937.7835	72266	1259
	Jiaozuo	1844.31	4071	368.4915	50050	905
	Luoyang	3284.57	15236	696.2300	47177	457
WJUB	Hefei	5180.56	11445	769.6000	67315	672
	Anqing	1544.32	15402	537.6000	28726	349
	Chuzhou	1214.39	13516	395.5000	30705	293
GCMR	Changsha	7824.81	11816	671.4121	116543	568
	Xiangtan	1570.56	5008	291.5000	53879	582
	Changde	2264.94	18910	608.6600	37212	322
WHUA	Wuhan	10069.48	8569	1033.0000	97478	1206
	Huangshi	964.25	4583	296.4600	32525	647
	Xianning	1218.56	9751	244.9200	49753	251
CCPL	Nanchang	3667.96	7402	517.7300	70847	699
	Jiujiang	1779.96	19078	513.1300	34688	269
	Shangrao	1550.20	22791	668.7968	23179	293

Source: GDP, Area, Population, GDP per capita, and Population density were derived from the statistical yearbook of corresponding city in 2015.

The total share of the population for these aggregated 18 cities compared to the nation's total population has increased from 6.38% in 2000 to 6.85% in 2014. In addition, the percentage of GDP increased from 6.45% in 2000 to 8.73% in 2012 with some fluctuations (Fig. 2A). We further compared the proportions of GDP and population for the three cities to those of the provinces (Fig. 2B and 2C). With the exception of TYUA, the growing concentration of GDP was observed in the other urban agglomerations. And in Hubei and Jiangxi province, more population was centered in our research area, namely WHUA and CCPL. However, the percentage of population in ZYUA accounted for an average of 17.76%.

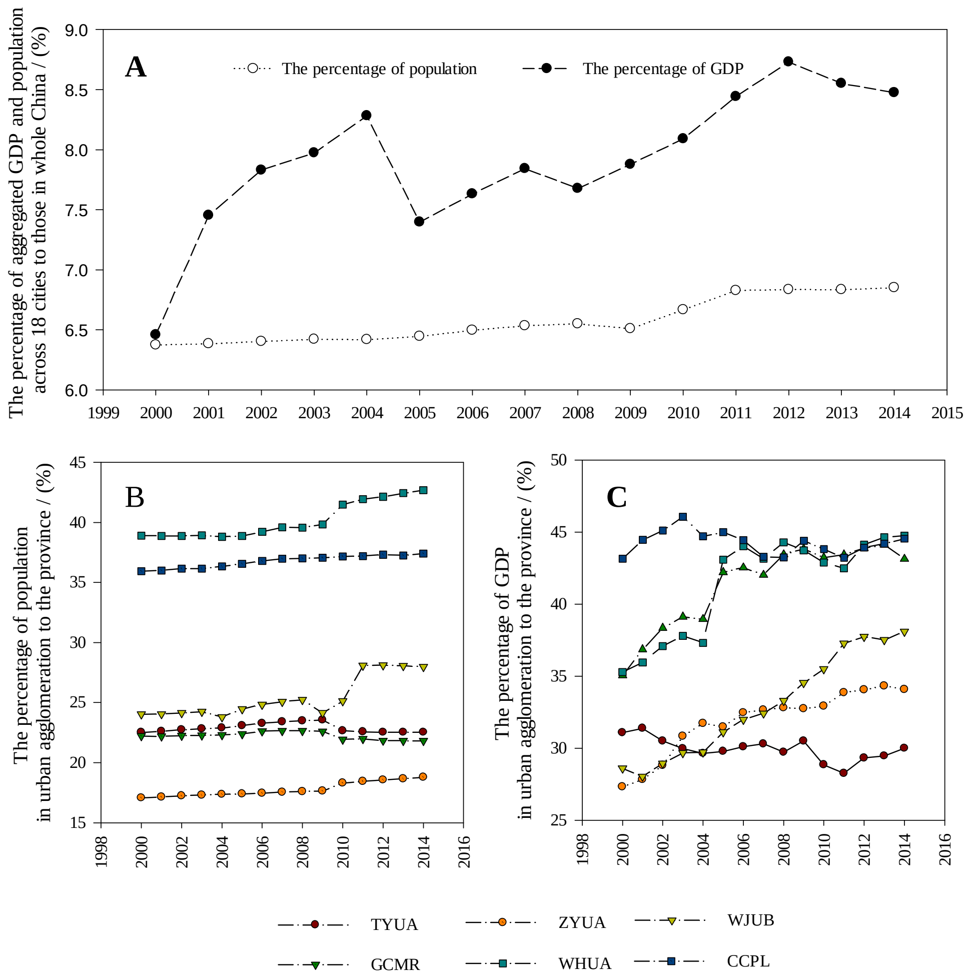

Fig.2. The percentage of aggregated 18 cities' GDP and population to the national's GDP and population (A) and urban agglomeration's population (B) and GDP (C) to those from the province during the period from 2000 to 2014.

2.2. Construction of CO_2 emission inventory

The specific method used to calculate the carbon emissions for each sector was discussed in our previous study(Shan et al., 2017), and only the most salient details are provided here.

To calculate the CO_2 emission inventory for each city, we need to define the boundary of the city (Bi et al., 2011; Cai and Zhang, 2014; Liu et al., 2015a; Satterthwaite, 2008). In this study, administrative territorial boundaries were considered the boundaries for the city's CO_2 emissions. These boundaries typically include urban centres, towns and rural populations (Dhakal, 2010; Wang et al., 2012). The emissions generated from fossil fuel combustion and industrial processes within the city are included. Energy consumed as chemical raw materials or lost during transportation is removed from the total energy consumption to avoid double counting. Emissions from electricity and heat generated within the city boundary are counted based on the primary energy input used, such as raw coal(Shan et al., 2017). Our administrative territorial emission inventory excludes emissions from imported electricity and heat consumption from outside the city boundary, as well as the energy consumed in inter-city transportation. We only focus on fossil fuel consumed within the city boundary(Shan et al., 2017).

2.2.1. Energy consumption

In this study, CO_2 emitted from energy consumption is calculated by multiplying the energy consumption of different socioeconomic sectors and the corresponding emission factors (Wang et al., 2012), as in Eq. (1).

$$CE_{energy} = \sum_j \sum_i CE_{ij} = \sum_j \sum_i (AD_{ij} \times EF_i) \qquad \text{Eq. (1)}$$

CE_{energy} represents the total CO_2 emissions resulting from fossil fuel combustion. $j \in [1, 47]$ indicates the socioeconomic sectors (see SI Table S1), which include primary industry (such as farming, forestry, animal husbandry, fishery and water conservation); secondary industry (such as manufacturing and the construction sector); tertiary industry (such as transportation, storage, post and communications, wholesale, retail sales, catering, trade and others); and residential consumption (such as urban and rural). Secondary industry was further decomposed into 40 sub-sectors, including mining, manufacturing, and electric power, gas and water production and supply. $i \in [1, 20]$ represents the energy types (Shan et al., 2017), and CE_{ij} denotes the CO_2 emissions derived from energy i in sector j. AD_{ij} represents the activity data (energy consumption), and EF_i refers to the emission factors of energy i. In this study, we adopt the emission factors recommended by Liu et al. (2015c), which are now widely used by other scholars (Mi et al., 2017; Shan et al., 2016a; Shao et al., 2016a).

2.2.2. Industrial processes

Carbon emissions from industrial processes mainly represent those emitted from the chemical and physical transformation of materials during industrial production, such as cement manufacturing and limestone consumption (Shan et al., 2016b; Wang et al., 2012). In the current study, the CO_2 emissions from industrial processes are emitted as the result of chemical reactions in the production process, not as the result of the energy used by industry. The equation describing these processes is shown in Eq. (2),

$$CE_{process} = \sum_t CE_t = \sum_t (AD_t \times EF_t) \qquad \text{Eq. (2)}$$

where $CE_{process}$ refers to the carbon emissions generated from the industrial process ($t \in [1, 7]$), and EF_t represents the emission factor for an industrial product. Most of the emission factors for industrial processes were collected from the IPCC (2006), while the emission factor for cement production was collected from our previous study (Liu et al., 2015c).

2.3. Data sources

The energy balance table (EBT) is a summary of energy production, transformation and final consumption (Shan et al., 2017; Shan et al., 2016c). The activity data (AD_{ij} and AD_t) were mainly obtained from the EBT of the statistical yearbook on Industry, Energy and Transport of the corresponding city. However, not all the cities' statistical yearbooks contained all the required data. The detailed calculation process and the updated emission factors for 2000 to 2014 followed previous research (Shan et al., 2017). The annual GDP data and city populations from 2000 to 2014 were derived from the statistical yearbooks of the corresponding cities. In addition, the GDP data in this study were standardized to currency values for the year 2000.

3. Results and discussion

3.1. Temporal and spatial variations in CO_2 emissions

Using the methodology described above and the data that we collected, we estimated the CO_2 emissions for 18 central Chinese cities for 2000-2014 (Fig. 3; Table S2). The results revealed that the total CO_2 emissions due to fossil fuel consumption and industrial processes for the aggregated 18 cities increased from 396.66 million tons (Mt) in 2000 to 1,145.19 million tons (Mt) in 2014, with an annual average growth rate (AAGR) of 7.87% (Fig. 3). The AAGR of CO_2 emissions in central Chinese cities was roughly consistent with the national growth rate (7%) (Geng et al., 2011b; Liu et al., 2015b). Additionally, the growth rate was lower during the periods from 2005 to 2010 (5.44%) and from 2010 to 2014 (5.61%) compared with that from 2000 to 2005 (12.23%). Trends were more evident in the provincial capital cities, where CO_2 emissions increased by 102.97%, 37.21%, and 18.49% from 2000-2005, 2005-2010, and 2010-2014, with AAGR values of 15.21%, 6.53%, and 4.33%, respectively. The increasing trend of CO_2 emissions demonstrated that with the ongoing economic development (the GDP increased from 640.85 billion Yuan in 2000 to 5458.39 billion Yuan in 2014) and technological progress, the consumption of fossil fuel and industrial production processes gradually switched to high-efficiency and energy-saving processes, resulting in the reduction of the AAGR.

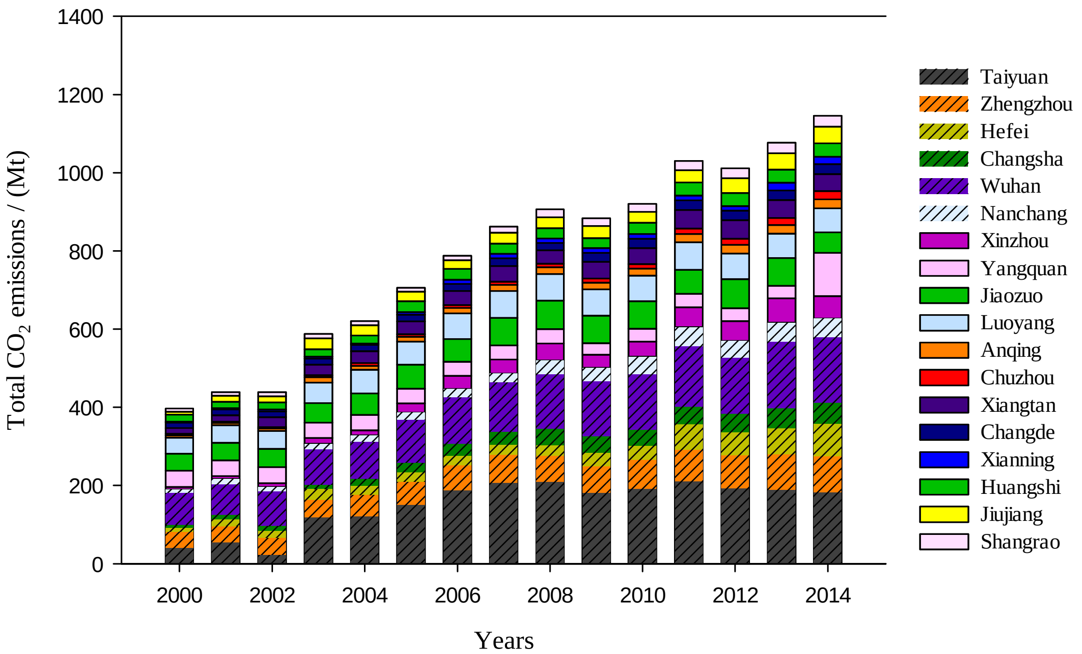

Fig. 3. Total CO_2 emissions for 18 central Chinese cities during the period from 2000 to 2014. **Note:** The legends

for provincial capital cities, including Taiyuan, Zhengzhou, Hefei, Changsha, Wuhan, and Nanchang, were filled with slash and presented to the bottom part.

Among the 18 cities, clear differences were seen in the CO_2 emissions over time (Fig. 4). The AAGRs for Hefei, Xinzhou, and Changsha increased rapidly, with values of 17.32%, 16.92%, and 15.08%, respectively (Fig. 4), due to rapid economic development and population centralization (Table 2). Conversely, Jiaozuo, Luoyang, Changde, Huangshi, and Wuhan developed with very low growth rates, with AAGRs of 1.37%, 2.82%, 4.12%, 5.05%, and 5.25%, respectively (Fig. 4). With the addition of Zhengzhou (5.85%) and Yangquang (7.29%), 7 of the 18 cities' AAGRs were below the average level (7.87%) (Fig. 4). However, the baseline CO_2 emissions for Wuhan and Zhengzhou in 2000 were higher than those of the other cities (Fig. 2; Table S2), indicating a faster industrialization process and an earlier awareness of environmental protection issues and CO_2 emissions mitigation and that strategies were proposed in these regions to control the vigorous growth of CO_2 emissions.

More attention should be paid to the dynamics of the emissions of Taiyuan, which relied heavily on coal and emitted the highest amount of CO_2. In 2000, the total CO_2 emissions varied from 2.95 Mt in Xianning to 82 Mt in Wuhan (Table S2). However, in 2003, the CO_2 emissions of Taiyuan (119.18 Mt) exceeded those of Wuhan (90.83 Mt) for the first time. After 2003, the emissions of Taiyuan have been higher than those of the other 17 cities, reaching a peak of 211.16 Mt in 2011 and gradually decreasing to 183.53 Mt in 2014 (Fig. 3).

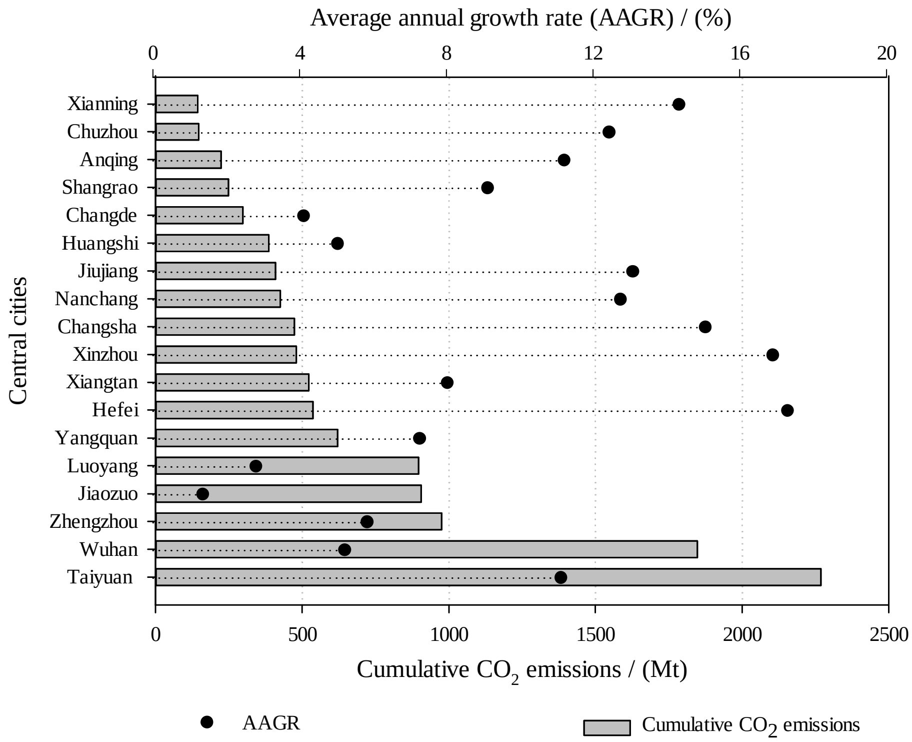

Fig. 4. The annual average growth rate (AAGR) and the cumulative CO_2 emissions of 18 central Chinese cities over the study period.

The two cities with the highest cumulative CO_2 emissions were Taiyuan and Wuhan, totalling

2268.57 Mt (19.21%) and 1847.59 Mt (15.64%), respectively, during the investigation period (Fig. 4). The emissions of Zhengzhou (975.49 Mt), Jiaozuo (904.99 Mt), Luoyang (896.80 Mt) accounted for the second highest proportions of the total among the 18 cities, with proportions of 8.26%, 7.66%, and 7.59%, respectively (Fig. 4). The overall percentage of CO_2 emissions for the six provincial capital cities accounted for more than one-half of the total emissions of the 18 cities after 2002, with the maximum proportion of 58.74% occurring in 2011 and the proportion decreasing to 54.77% in 2014 (Fig. 3). The increasing proportion of CO_2 emissions from the provincial capitals indicated that energy consumption has been concentrated in the provincial capitals with the progression of economic development. Furthermore, the share of CO_2 emissions for the provincial capital cities relative to the urban agglomerations increased from 46.77% in 2000 to 52.29% in 2014 for the TYUA, 32.49% to 44.33% for the ZYUA, 48.95% to 65.37% for the WJUB, and 20.57% to 43.90% for the GCMR, 36.06% to 40.33% for the CCPL. A slight decrease for the WHUA was observed, from 80.40% to 75.9% (Fig. 3). Additionally, the share of cumulative CO_2 emissions for provincial capital cities relative to their respective urban agglomerations was highest in the WHUA, at 77.67%, followed by the TYUA (67.32%) and the WJUB (59.13%), for the study period. However, not all CO_2 emission values were higher in provincial capital cities than in non-provincial capitals, such as in the GCMR, where the cumulative CO_2 emissions from Changsha (472.98 Mt) were lower than those of Xiangtan (523.20 Mt) (Fig. 3; Table S2). The CO_2 emissions of Changsha surpassed those of Xiangtan in 2008.

The spatial distribution of CO_2 emissions has remained nearly stable over the past 15 years and is noticeably uneven among cities (Fig. 5). In 2000, Wuhan ranked the highest at 82 Mt of emissions, accounting for above one-fifth of the 18 cities' total CO_2 emissions. The other five cities, including Jiaozuo, Taiyuan, Luoyang, Yangquan and Zhengzhou, primarily located in ZYUA and TYUA, each emitted more than one-tenth of the total CO_2 emissions (Fig. 5). In 2014, the high-emission centres remained in the same places; however, between 2000 and 2014, the percentage of CO_2 emissions for individual cities changed. Except for Taiyuan and Hefei, in which emissions increased from 10.54% and 2.26% in 2000 to 16.03% and 7.33% in 2014, respectively, the proportions of CO_2 emissions for the remaining four provincial capital cities declined overall. In Wuhan, the proportion decreased from 20.67% to 14.56% (Fig. 5).

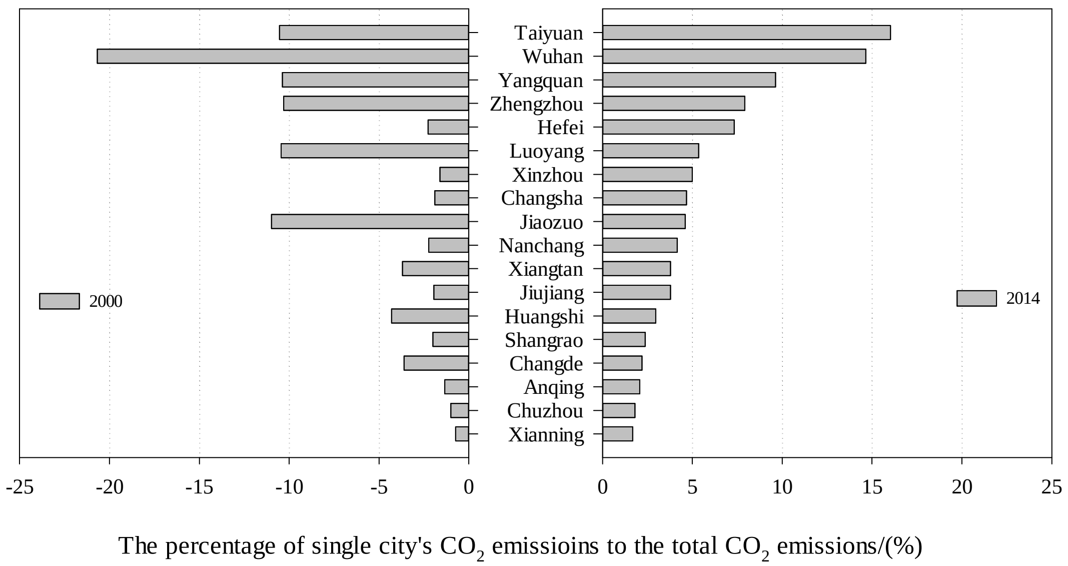

Fig. 5. The percentage of single city's CO_2 emissions to the total CO_2 emissions with the years of 2000 and 2014.

The emissions by sector and fossil fuel type, as well as by socioeconomic characteristics, are discussed below to provide a deep understanding of the energy utilization structure and the factors influencing carbon emissions.

3.2. Emissions by sector and fossil fuel type

Fig. 6A depicts the percentage of sectoral cumulative CO_2 emissions for six urban agglomerations. To further analyse the amount and proportion of sectoral CO_2 emissions, Fig. 6B describes the distribution of CO_2 emissions by sector for different cities in 2014. To compare the various sectors' CO_2 emissions at another scale, we merged 47 socioeconomic sectors into 12 categories (Table S1)). The results show that "power generation" represented the largest share of the total cumulative CO_2 emissions, accounting for an average of 36.51% among the 18 cities. In Beijing, the production and supply of electric power and steam power also accounted for 32% of the total direct carbon emissions (Shao et al., 2016b). The "non-metal and metal industry", and "petroleum and chemical industry", and "mining" sectors accounted for the second largest proportions of total CO_2 emissions, at 29.81%, 14.79%, and 9.62%, respectively. The CO_2 emissions generated from "mining" in the TYUA, representing the highest contribution of 28.21% over the whole period, were higher than those derived from "power generation", especially in Taiyuan and Yangquan (Fig. 6). In addition, with the progression of urbanization, the "petroleum and chemical industry" and "mining" sectors gradually yielded to "power generation" in Taiyuan, with the percentages shifting from 30.74%, 31.83%, and 16.06% in 2003 to 22.91%, 28.21%, 26.39%, respectively, in 2014.

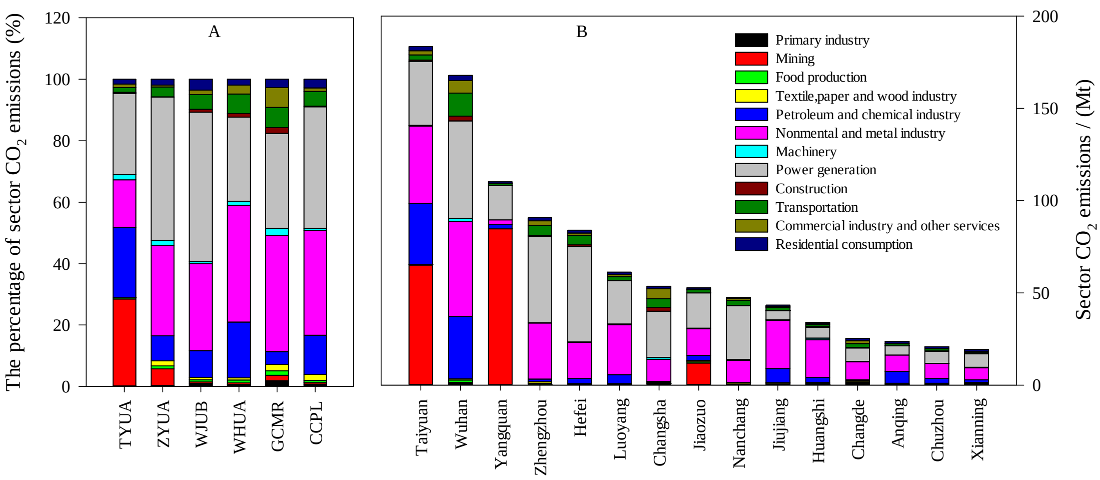

Fig. 6. The percentage of cumulative sectoral CO_2 emissions within six urban agglomerations over the whole period (A) and CO_2 emissions by sector in different cities in 2014 (B).

The average CO_2 emissions from SI (secondary industry) accounted for the largest share of the total CO_2 emissions, ranging from 78.72% in Changsha to 95.01% in Taiyuan (Fig. S1). The contribution of SI to the total GDP was 48.69% and 44.18% in Changsha and Taiyuan, respectively, indicating that an industrial structure shift from SI to tertiary industry (TI) could be beneficial not only in increasing the GDP but also in reducing carbon emissions. Three categories of relationships between the contributions of SI to the total GDP and CO_2 emissions were observed. First, a decrease in the percentage of SI-related CO_2 emissions occurred with increasing contributions of SI to GDP. Cities in this category included Wuhan, Zhengzhou, and Changsha. Second, the proportion of SI-related CO_2 emissions increased with SI contributions to GDP. Hefei and Nanchang belonged to this category. Third, the industrial structure and the contribution of SI-related CO_2 emissions remained roughly stable, such as in Taiyuan (Fig. S1).

Fig. 7A presents the proportion of CO_2 emissions from fossil fuel combustion and industrial processes for six urban agglomerations for the study period. Fig. 7B presents the CO_2 emissions from the different energy types for six provincial capital cities in 2014. The primary source of CO_2 emissions was the use of raw coal, which contributed an average of 60.93% of the total in the central region, followed by clean coal, which represented an 8.25% contribution. The contributions of coke and crude oil to the total CO_2 emissions were 6.22% and 4.54%, respectively. Previous research also found that the share of CO_2 emissions from coal combustion was approximately 70% from 2005-2008 (Geng et al., 2011b) and 80% from 2000-2013 (Liu et al., 2015a). By merging 20 energy types into 3 categories, including coal, oil, and natural gas, we further analysed the CO_2 emissions by energy type (Fig. S2).

It is well known that coal is a high-emission fossil fuel compared with crude oil and natural gas since it emits more CO_2 to produce the same amount of heat compared with the other energy types (Li et al., 2010). In the TYUA, 95% of the CO_2 emissions were generated from coal combustion, while 0.53% were from natural gas (Fig. 7A), which is why Taiyuan, which largely relied on coal, contributed the most to the total CO_2 emissions. Among the coal-related CO_2 emissions, the contribution of “mining” in Taiyuan accounted for 55% in 2014 followed by “power generation”. In the other five provincial capital cities, the “power generation” sector contributed the most to the raw CO_2 emissions, especially in Nanchang, where power generation had the largest share at 95%. Taking 2014 as an example, the raw coal-related CO_2 emissions were higher in Taiyuan than those of the other provincial capital cities, and the emissions from Taiyuan were larger than the total CO_2 emissions from Zhengzhou, Hefei, Changsha and Nanchang (Fig. 7B).

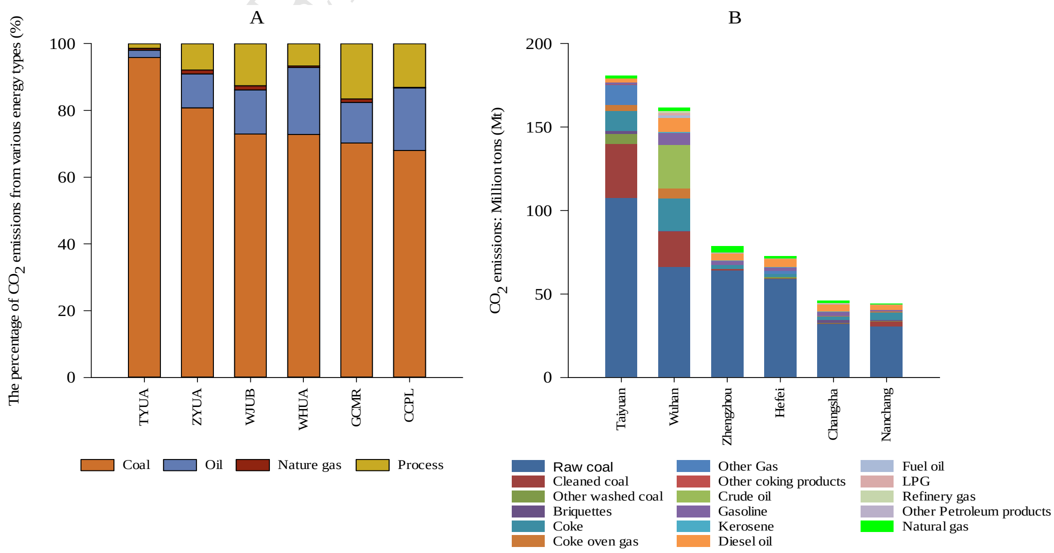

Fig. 7. The percentage of CO_2 emissions by energy types and industrial process (%) during the investigation period (A) and CO_2 emissions by energy types from six provincial capitals in 2014 (B).

Although the CO_2 emissions from coal gradually increased, the proportion of coal-related emissions decreased due to improvements in the energy mix (Geng et al., 2011b). Similar results were found in our study. Taking Zhengzhou as an example, the coal-related CO_2 emissions increased from 34.13 Mt in 2000 to 67.33 Mt in 2014. However, the percentage of coal-related CO_2 emissions dropped from 94.14% to 85.69, oil-related CO_2 emissions increased from 5.78% to 9.7%, and natural gas-related CO_2 emissions increased from 0.07% to 4.61% (Fig. S2). In 2015, coal remained the dominant fuel, accounting for 64% of China's energy consumption, and this was the lowest share on record, representing a decrease from a high of 74% in the mid-2000s. Coal production fell by 2% compared to the 10-year average growth of 3.9%. However, the production of other fossil fuels grew: natural gas production increased by 4.8% and oil production increased by 1.5%. China's CO_2 emissions from energy use declined by 0.1% in 2015, the first decline in emissions since 1998 (BP, 2016).

Industrial processes also played a significant role in determining CO_2 emissions and represented an average of 7.3% of the total emissions over the study period, which is consistent with the results reported by Olivier et al. (2013). The percentage of emissions generated from industrial processes varied from 0.96% in Xinzhou to 31.58% in Shangrao due to differences in economic development and energy structure.

3.3. Preliminary analysis of factors influencing carbon emissions

Generally, economic development and population expansion have increased CO_2 emissions (Geng et al., 2011b; Li et al., 2010). To allow for comparisons among cities and to identify the extent to which the economy and population depend on energy, we normalized the total CO_2 emissions on per capita and per GDP bases (Wang et al., 2012).

The average CO_2 emissions per capita across the 18 cities increased from 6.14 metric tons in 2000 to 15.87 metric tons in 2014, corresponding to a 158.69% expansion, which appeared higher than the total values for China and the world (Fig. 8). This increase puts tremendous pressure on local governments as they seek to realize their carbon emission reduction ambitions (Wang et al., 2012). The average per capita CO_2 emissions in this study were 2.27 times higher than those of China and 1.52 times higher than those of the world in 2000 and were 1.7 and 2.5 times higher, respectively, in 2012 (Fig. 8). In addition, the per capita CO_2 emissions of central Chinese cities, such as Taiyuan, Yangquan, Jiaozuo, Wuhan, were higher than those of highly urbanized cities as Shanghai, Beijing, Tianjin emitted 12.8, 10.7, and 11.9 t CO_2-eq/capita, respectively, in 2006 (Sugar et al., 2012). Therefore, reducing the per capita carbon emissions in the central region is very important given the carbon mitigation targets of China and the world. The result of this comparison reveals that some Chinese cities have already emitted more CO_2 than cities abroad, not only in terms of total quantity but also per capita (Yu et al., 2012).

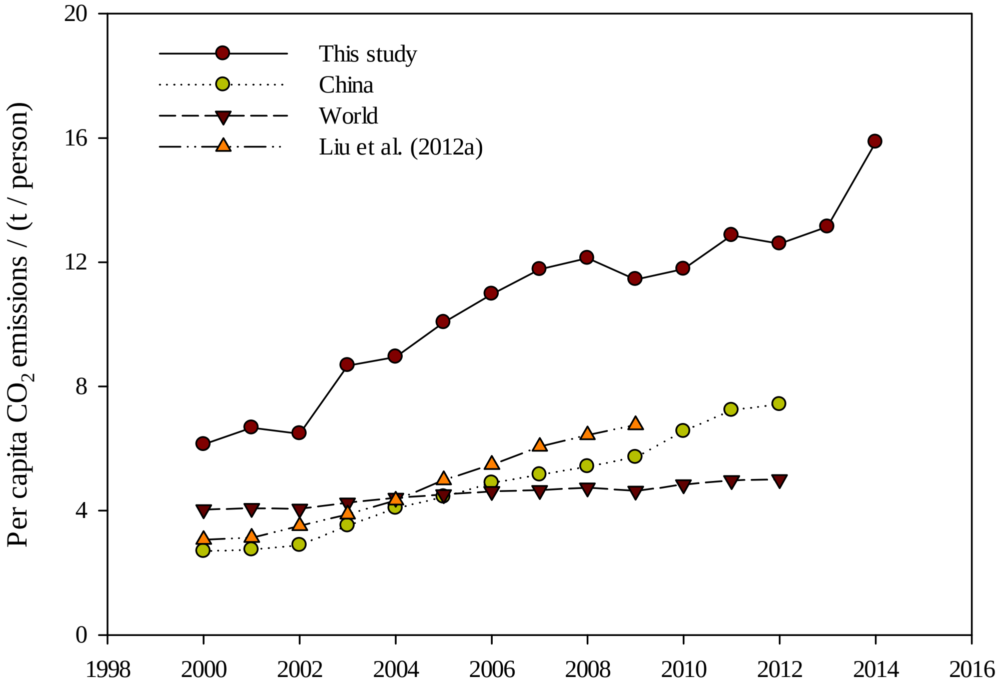

Fig. 8. The average per capita CO_2 emissions across various scales. Note: The data of China and world were obtained from Carbon Dioxide Information Analysis Center, Environmental Sciences Division, Oak Ridge National Laboratory, Tennessee, and United States. The data of positive triangle of orange were obtained from Liu et al. (2012a)

The increasing tendency of per capita CO_2 emissions differed among individual cities due to differences in development stages and pathways. The AAGR of per capita CO_2 emissions increased rapidly in Xinzhou (16.39%), Changsha (13.93%), Xianning (13.81%). However, the per capita emissions in Jiaozuo exhibited a slow growth rate of 0.55% per year during the observation period, which coincided with the lower growth rate of total CO_2 emissions (AAGR: 1.37%) (Fig. 4 and Fig. 9). Per capita CO_2 emissions represent not only an individual's lifestyle choices but also the nature of local infrastructure and the structure of the economy in a given geographical region (Hoornweg et al., 2011). Among the six provincial capital cities, the per capita CO_2 emissions were consistently above average for Taiyuan and Wuhan and were below average for the other four provincial capitals over the study period (Fig. 9). Taiyuan, the capital city of Shanxi, is the headquarters of the China National Coal Group Corporation. In addition, Wuhan is a critical industrial base in China and is home to many industries, including iron and steel, automobile, electronics, chemical industry, metallurgy, textiles, shipbuilding, manufacturing, medicine and other industrial sectors. Consequently, these two cities have the highest CO_2 emissions. Although Taiyuan and Wuhan emitted the largest amounts of CO_2 in 2014, and these amounts were approximately the same at 183.53 Mt and 167.77 Mt (Fig. 2; Table S2), respectively, the population of Wuhan was 2.8 times larger than that of Taiyuan (Table 1). In addition, the per capita emissions from Taiyuan were 3 times higher than those from Wuhan (Fig. 9). Interestingly, the per capita CO_2 emissions in Taiyuan decreased from a peak of 58.15 metric tons in 2008, which was 3 times higher than the average level in 2014 (Fig. 9). However, the per capita CO_2

emissions in other foreign cities decreased. For example, the average rate of reduction in the per capita emissions for six cities, including Berlin, Boston, Greater Toronto, London, New York City and Seattle, was 0.27 t CO_2e/capita per year for the period of 2004-2009. In addition, this decrease appeared in these six cities mainly due to changes in stationary combustion sources (Kennedy et al., 2012).

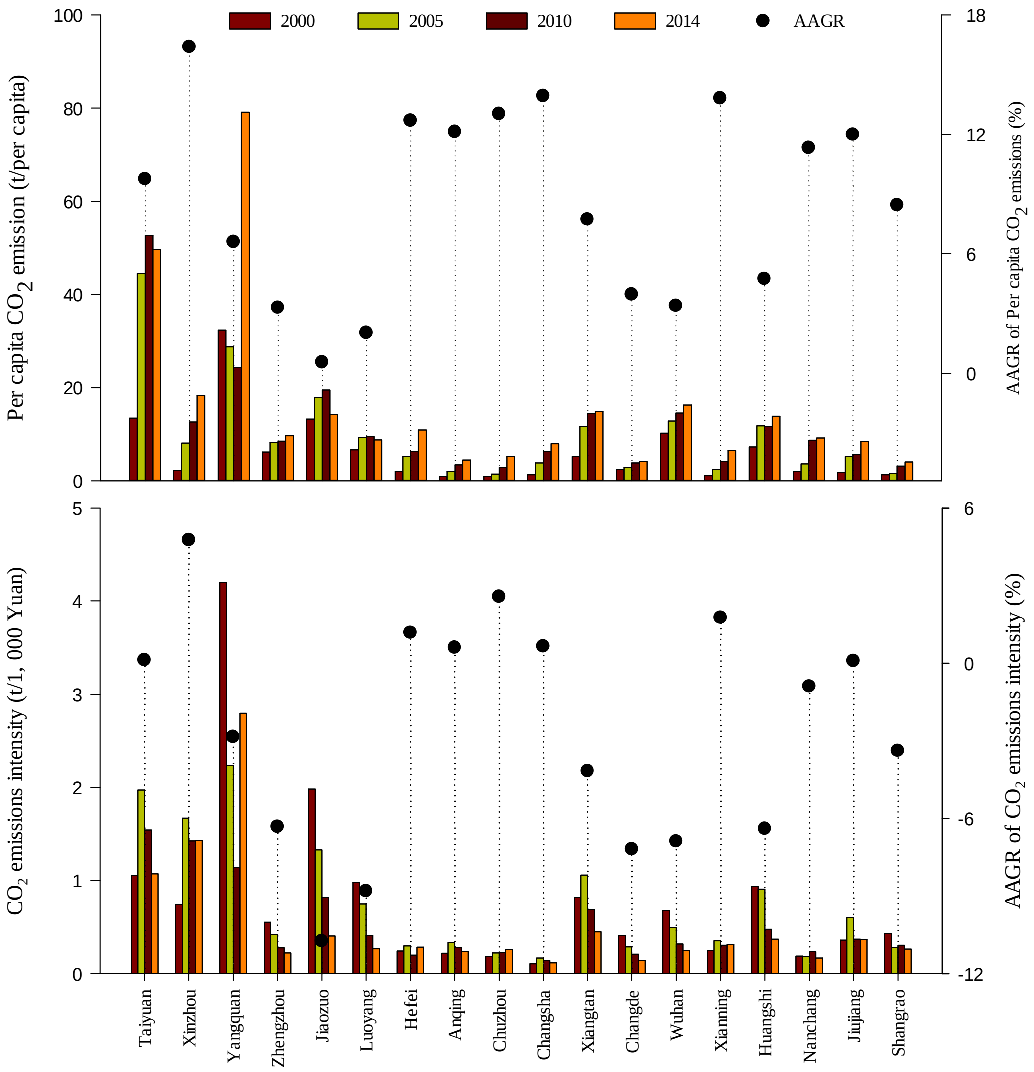

Fig. 9. The per capita CO_2 emissions, and CO_2 emissions intensity, and AAGR of these two factors for 18 central Chinese cities with the years of 2000, 2005, 2010, and 2014.

The emissions intensity and AAGR for individual cities are shown in Fig. 9. Although total CO_2 emissions have increased over the past 15 years, the average CO_2 emission intensity decreased from 0.8 metric tons/1,000 Yuan in 2000 to 0.52 metric tons/1,000 Yuan in 2014, with some fluctuations (Fig. 9). The primary reason for the reduction in emission intensity is that the GDP grew faster than emissions (Fig. 10). The total GDP and CO_2 emissions increased by 454.61% and 188.71%, with annual growth rates of 13.02% and 7.87%, respectively, during the period from 2000 to 2014 (Fig. 10). With the exception of the TYUA, the average CO_2 emission intensity appeared to be lower than 0.5 metric tons/1,000 Yuan in the other 15 cities in 2014 (Fig. 9), with values ranging from 0.11 to 0.45 metric tons/1,000 Yuan. The TYUA, located in Shanxi province, was recognized as the largest coal producing region. However, instead of retaining large profits, the TYUA supplied coal to the other regions; therefore, although the GDP of this region was not very high, the TYUA had the largest amount of coal consumption and consequently the highest CO_2 intensity (Geng et al., 2011b). The results presented in this study align with those of Liu et al. (2015a), who illustrated that developed regions possess both higher total emissions and per capita emissions with lower emission intensity. The national average CO_2 emission intensity in 2012 was 0.15 metric tons/1,000 Yuan, and the value in the central region was 0.2 metric tons/1,000 Yuan (Shan et al., 2016c). However, the value in this study was 0.46 metric tons/1,000 Yuan, which was higher than that of the central region and of China as a whole. Consequently, more efforts should be taken to increase the use of low-carbon energy and clean energy and to reduce the carbon emission intensity in these 18 cities, such as changing energy consumption. The emission intensities of the PI, SI, and TI decreased from 2000 to 2014, especially for the SI in Wuhan and Zhengzhou, which had AAGRs of -10.58% and -10.29%, respectively (Fig. S1).

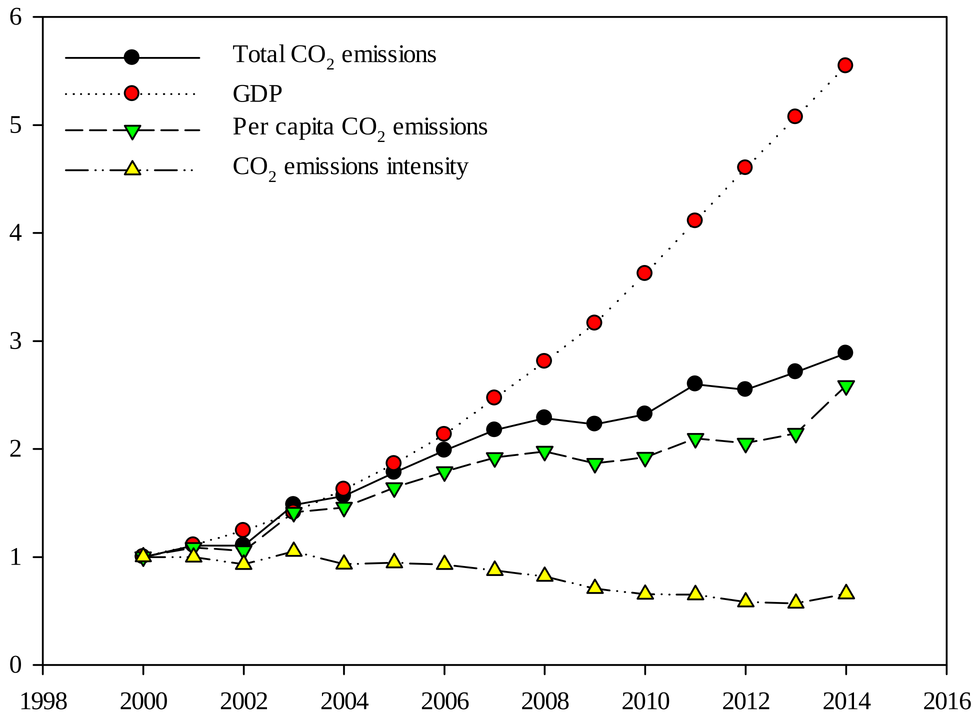

Fig. 10. The changes of total CO_2 emissions, GDP, per capita CO_2 emissions, and CO_2 emission intensity from 2000 to 2014. Levels for 2000 are set to 1 for all indicators.

Previous research has illustrated that different emission intensities in different regions are the result of critical differences in technology (Li et al., 2010; Liu et al., 2012a). Industrial structure and energy efficiency have also been found to be the primary factors determining emission intensity (Su et al., 2014). The share of tertiary industry has a positive effect in curbing carbon emission intensity (Zhang et al., 2014). The average CO_2 emission intensity in Taiyuan (1.53 metric tons/1,000 Yuan) was approximately 10 times higher than that of Changsha (0.14 metric tons/1,000 Yuan). As discussed above, the dependence on coal and oil and the utilization of clean energy together resulted in higher CO_2 emissions in Taiyuan. In this study, the sectoral CO_2 emissions from "coal mining and dressing" and "petroleum processing and coking" amounted to 581 and 502 Mt for Taiyuan and 4.4 and 0.1 Mt for Changsha, respectively, in 2014 (Fig. 6).

China has adopted the target of reducing the CO_2 emissions per 1,000 Yuan of GDP by 40-45% relative to 2005 levels by 2020 (xinhua, 2015). Previous research found that the CO_2 emissions per unit GDP fell by 28.5% from 2005 to 2013 (Liu et al., 2015b). In addition, the achievement of the carbon emission reduction targets proposed by national governments relies on provincial, state, city and regional allocations and their actions (Bai et al., 2014). In this study, the average CO_2 intensity decreased from 0.75 metric tons/1,000 Yuan in 2005 to 0.52 metric tons/1,000 Yuan in 2014, a decrease of approximately 30% (Fig. 9). The national's CO_2 emission reduction targets have not been achieved ahead of time across the 18 cities. In fact, eight of the 18 cities were above the national average (40%).

4. Policy implications and conclusions

This study applies a practical methodology to construct territorial CO_2 emissions inventories of 18 central Chinese cities located in six urban agglomerations for the period from 2000 to 2014. The reasons for choosing central China are summarized as follows. First, with the proposal and implementation of the Rise of Central China Strategy after 2004, the central region experienced rapid economic development. However, this region must ask how it can avoid the environmental problems resulting from its extensive development. In other words, methods for controlling the CO_2 emissions originating from fossil fuel combustion, especially in Shanxi, which relied heavily on coal, should be taken into consideration. Second, a larger proportion of the population in central China, especially in Henan, consumed more energy. Thus, the development of methods for reducing per capita emissions is both urgent and vital. Based on the above considerations, we found that the population and GDP for the selected 18 cities accounted for an average of 6.57% and 7.91% of China's total population and GDP, respectively, during the investigation period (Fig. 2A). However, the share of the CO_2 emissions of these cities in various studies is on average 13.38% of China's total CO_2 emissions (Shan et al., 2016c) , which is higher than the proportions of GDP and population. Although the total CO_2 emissions increased from 396.66 Mt in 2000 to 1145.19 Mt in 2014 (Fig. 3), the AAGR of total CO_2 emissions gradually decreased, with values of 12.23%, 5.44% and 5.61% for 2000-2005, 2005-2010, and 2010-2014, respectively (Fig. 3). With respect to the individual capital cities, the AAGR of total CO_2 emissions ranged from 17.32% in Hefei to 5.25% in Wuhan. The relationships between GDP, population, energy and industrial structures, and CO_2 emissions are summarized as follows.

Economic development has positive effects on CO_2 emissions and vice versa (Guan et al., 2017; Wang et al., 2012; Zhang and Da, 2015; Zhang et al., 2014). For example, among the six provincial capital cities, Wuhan has higher cumulative CO_2 emissions (Fig. 4), per capita GDP (Table 1), and per capita CO_2 emissions (Fig. 9), while Nanchang has lower cumulative CO_2 emissions (Fig. 3), per capita GDP (Table 1), and per capita CO_2 emissions (Fig. 9). The base amount of CO_2 emissions in 2000 for Wuhan was approximately 10 times that for Nanchang (Fig. 3-5; Table S2), at 82 and 8.85 Mt, while in 2014, the values reached 167.77 and 47.57 Mt, respectively (Fig. 3-5; Table S2). In addition, the CO_2 emissions of Nanchang grew faster than those of Wuhan (Table 2). The levels of economic and social activity, as well as the systems and structures that enable such activities, provide data regarding the amount of CO_2 emissions (Sugar et al., 2012). Although the contribution of SI-related GDP increased in Wuhan, the SI-related CO_2 emissions decreased from 94.18% in 2000 to 86.34% in 2014 due to improvements in technology and adjustments in industrial structures, while the share of TI-related CO_2 emissions increased from 5.35% in 2000 to 13.11% in 2014. Because of Wuhan's high-quality higher education, the high-tech and new technology sectors, represented by the Optical Valley, have developed well. Moreover, the number of listed companies within Wuhan reached 50 in 2015, ranking it eleventh among Chinese cities (Yicai, 2016), and these companies contributed the largest share of the GDP of Wuhan. As discussed above, TI plays a significant role in improving energy efficiency and reducing carbon emissions (Guan et al., 2017; Zhang et al., 2014), and the presence of these industries is the reason why the AAGR of emission intensity in Wuhan greatly decreased during the investigation period (9.55%) (Table 2). Consequently, Wuhan was able to maintain or even decrease its CO_2 emissions while increasing its economic development and population. Contrary to Wuhan, the industrial structures of Nanchang changed from PI and TI to SI, which increased the share of SI-related CO_2 emissions. Furthermore, the AAGR of the GDP of Nanchang was also lower compared to the other six capital cities. Thus, Nanchang was focused on quickly developing its economy while controlling the growth of CO_2 emissions.

Table 2 The AAGR of total CO_2 emissions, GDP, population, per capita GDP, Per capita emissions, and CO_2 emission intensity for six provincial capital cities during 2000 to 2014.

	Total CO_2 emissions	**GDP**	**Population**	**Per capita GDP**	**Per capita emission**	**CO_2 emission intensity**
Taiyuan	11.14	14.16	1.27	11.40	9.75	-2.64
Zhengzhou	5.85	17.16	2.48	14.31	3.30	-9.65
Hefei	17.32	20.76	4.10	16.57	12.69	-2.85
Changsha	15.08	18.63	1.01	17.18	13.93	-3.00
Wuhan	5.25	16.36	1.80	14.30	3.39	-9.55
Nanchang	12.76	15.89	1.29	14.28	11.33	-2.70

Economic development has a negative relationship with CO_2 emissions (Zhang and Cheng, 2009). For example, Taiyuan had higher CO_2 emissions (Fig. 3-5; Table S2) and per capita emissions (Fig. 9) but a lower per capita GDP (Table 1). In contrast with Taiyuan, Changsha had lower CO_2 emissions (Fig. 3-5; Table S2) and per capita emissions (Fig. 9) but a higher per capita GDP (Table 1). The cumulative CO_2 emissions of Taiyuan were 4.7 times higher than those of Changsha (Fig. 4), and in 2014, these two cities emitted 183.53 and 53.61 Mt (Table S2), while the GDP and permanent resident population were 3.1 and 1.8 times lower, respectively, than those of Changsha (Table 1). Therefore, higher emission intensity and higher per capita CO_2 emissions were found in Taiyuan (Fig. 9). The average SI-related CO_2 emissions in Taiyuan were largest among the six provincial capital cities at 95.01%. The economic activities of Taiyuan relied heavily on intensive resource mining, such as coal (97.44%; Fig. S2), resulting in the largest amount of CO_2 emissions in the central region (Liu et al., 2012a). Thus, it is necessary to change the energy structure and accelerate the process of industrial upgrades in Shanxi. For example, shifting energy consumption from coal to a greater share of clean energy, such as natural gas, hydropower, and solar, has been effective in controlling CO_2 emissions (Geng et al., 2011a; Li et al., 2010; Sugar et al., 2012). Additionally, large-scale coal mine construction should be encouraged, electricity and grid construction should be accelerated and raw materials processing should be vigorously developed.

From the perspective of industry, the number of listed companies is one of the most important indicators for measuring the competitiveness of a city and promoting the growth of GDP. In 2015, Changsha was home to 49 listed companies, ranking 12th in China followed by Wuhan. However, Taiyuan ranked out of 50th (Yicai, 2016). Consequently, although the share of SI-related GDP for Changsha increased from 40.8% in 2001 to 54.2% in 2014, the contribution of SI-related CO_2 emissions decreased from 81.23% to 76.92%. Therefore, although the total CO_2 emissions were not as high as those for Taiyuan, this city still needs to control the growth of total CO_2 emissions (Table 2) resulting from the concentration of the population into the provincial capital city (Fig. 2).

In terms of cumulative CO_2 emissions, Zhengzhou ranked third among the 18 selected cities, contributing 8.26% of the total CO_2 emissions, followed by Taiyuan and Wuhan (Fig. 4). The GDP in Zhengzhou also ranked third in 2014, followed by Wuhan and Changsha (Table 1). As the capital city of the most populous province, the permanent resident population of Zhengzhou reached 9.38 million, ranked second among the 18 cities in 2014 (Table 1). Despite the lower AAGR of the CO_2 emissions of Zhengzhou (Table 2), the base amount of CO_2 emissions in 2000 was still high (Fig. 3; Table S1). Thus, Zhengzhou still needs to control its total amount of CO_2 emissions. The total amount of CO_2 emissions from coal use increased, with the share dropping from 94.14% in 2000 to 85.69% in 2014 due to energy and industrial restructuring (Fig. S1). The three industry structures for Zhengzhou changed from 3.1:54.5:42.4 in 2010 to 2.1:49.5:48.4 in 2015, indicating that TI continued to rise, while the PI and SI declined to a certain degree. Furthermore, the proportion of industrial value added for six energy-intensive industries to the industrial enterprises above decreased from 51.4% in 2010 to 40.2% in 2015 (Zhengzhou, 2016). In addition, in this study, the share of SI-related CO_2 emissions decreased from 94.09% in 2000 to 89.09% in 2014. The increasing share of tertiary industry and decreasing share of energy-intensive industry together contributed to lower coal-related CO_2 emissions(Guan et al., 2017). Formally approved by the state council, Wuhan and Zhengzhou were recognized as the national central cities in 2016 (xinhua, 2017), likely because the per capita emissions grew slowly and because their CO_2 emission intensities rapidly decreased from 2000 to 2014 (Table 2).

The AAGRs of total CO_2 emissions, GDP, and population appeared to be the highest in Hefei among the six provincial capital cities (Table 2). Avoiding the fast growth of CO_2 emissions was clearly a primary objective for Hefei. The coal-related CO_2 emissions of Hefei increased from 7.9 Mt in 2000 to 63.67 Mt in 2014, among which raw coal contributed most. However, the share of raw coal increased until 2003, with a peak value of 96.96%, and then began to decrease. In 2014, the percentage contribution of raw coal was 87.65%. Conversely, the contribution of CO_2 emissions from gas increased over the investigation period (Fig. S2).

With regarding to the cities, like Zhengzhou and Wuhan, the baseline of CO_2 emissions were higher and the AAGR of CO_2 emissions were lower in the central regions. The primary mission was to further shift industry structure from second industry to tertiary industry, and adjust the energy types from coal to the clean energy types in order to keep the economy healthy growing under the premise of controlling the rapid growth of CO_2 emissions. For Changsha and Hefei, how to control the vigorous growth of CO_2 emissions, was the main task. Consequently, it was urgent to improve the energy efficiency, change the extensive development pattern into intensive pattern. With respect to Taiyuan, high energy consumable industries should be effectively control, small-scale coal mine construction should be prohibited, electricity and grid construction should be accelerated and raw materials processing should be vigorously developed.

Acknowledgments

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