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A Comparative Decomposition Analysis of the Factors Driving Energy-related Carbon Emissions from Three Typical Provinces in China: Jiangsu, Henan and Inner Mongolia

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Abstract: An accurate understanding of the real situation of energy-related carbon emissions and the main factors driving the carbon emissions increments are crucial for China to realize its emission mitigation targets. Adopting the comparative decomposition of an extended LMDI (Log-Mean Divisia Index) approach, this study decomposed the changes in carbon emissions of Jiangsu, Henan, and Inner Mongolia, which are located in the eastern, central and western parts of China. This analysis led to three main findings. 1) During the period of 1996–2017, the energy-related carbon emissions in the examined provinces exhibited upward trends, but with some differences among the provinces. 2) The influences of driving factors on carbon emissions varied distinctly in different provinces and economic stages. Economic growth had the largest positive effect on provincial carbon emissions increases. From 1996 to 2017, the contribution rates of economic development to emissions growth in Henan, Jiangsu and Inner Mongolia were 307.19%, 205.08% and 161.26%, respectively. This influence was followed by urbanization and population size. 3) Energy intensity played a leading role in facilitating emissions-reduction in the examined provinces, except for during the tenth Five-Year Plan, followed by the energy structure. The effect of rural population proportion was the weakest among all the curbing factors. Furthermore, urban and rural resident′s energy consumption per capita demonstrated relatively minor impacts and disparate directions of influence in the different provinces and economic periods, but began to play increasing roles in driving up provincial emissions changes. For example, residential energy consumption in Jiangsu contributed over 7.9% to the total carbon emission growth in 1996-2017, among which urban residents' per-capita energy consumption contributed more than 3.8%. In view of these findings, policy makers should formulate targeted emission reduction measures that are based on the distinct situations and key factors which affect carbon emissions in each province.

Key words: carbon emission; decomposition analysis; LMDI method; China's typical provinces

1 Introduction

With the rapid development of the social economy, CO_2 emission from energy consumption has become one of the main factors driving climate change. Reducing carbon emissions and developing a low-carbon economy are attracting increasing attention from the international community. According to statistics from the International Energy Agency (IEA), China's carbon emissions in 2017 accounted for 27.3% of total global CO_2 emissions and exceeded the sum of those of the US and EU (Liu et al., 2020). As a responsible country, the Chinese government promised a target of reducing the per unit gross domestic product (GDP) carbon emissions by 60%–65% in 2030 compared with the 2005 levels (Wen and Shao, 2019). The realization of this goal depends not only on the low-carbon transformation of economic development, industrial restructuring and techno-

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logical progress at the national level, but also to a large extent on the coordinated emission reduction actions at the provincial level. However, across China's different provinces there are great gaps in social-economic development levels, industrial structure, resource endowment, and residents' energy consumption and demographic structure, resulting in significant differences in carbon emissions. On the other hand, with the accelerated process of industrialization, the difficulty and the cost of emission reduction are also increasing. Besides, the rapid transformation of population structure, the rapid decline of the rural population proportion and the rise of energy consumption by residents have all brought great pressure to China's emission mitigation. Accordingly, from the premise of maintaining healthy and stable economic growth, controlling the total carbon emissions of China's provinces, scientifically allocating emission reduction tasks in each province, and ultimately achieving the overall national emission reduction goals, are the issues that the government must consider when formulating differentiated emission reduction measures. Thus, it is necessary to deeply explore the factors driving regional or provincial carbon emissions growth during the process of China's economic development, and their relative contributions.

Many scholars have studied the factors driving changes in carbon emissions. Paul and Bhattacharya (2004) found that a fast-growing economy was the most important factor contributing to the increase of carbon emissions. By testing the relationship between global carbon emissions and population, Birdsall (1992) believed that population expansion leads to more energy demand and land-use change, resulting in the increase of carbon emissions. Dalton's research showed that in the first half of the 20th century, the net impact of technological progress played a prominent role in the carbon emissions increase, while the net impact of population aging was a reduction in carbon emissions, and under certain conditions, the effect of population aging on carbon emissions was more significant than that of technological progress (Dalton et al., 2008). Shrestha et al. (2009) studied the factors driving carbon emissions from the power industry in 15 major countries in the Asia-Pacific region using the LMDI method of decomposition. They found that economic growth was the dominant factor responsible for the increase in carbon emission in ten of the selected countries, while the increasing power intensity was the main factor driving carbon emissions in three of the countries (Bangladesh, Indonesia and Philippines), and the energy structure played a major role in the remaining two countries. Sheinbaum et al. (2010) used international comparisons and LMDI to analyze energy and carbon emission trends of Mexico's iron and steel industry during the period of 1970–2006. Suh (2018) used the entropy approach to study the regional differences of carbon dioxide emissions and found that the inequalities of CO_2 emissions varied across the regions in the United States.

The research on the forces driving carbon emissions in China can be traced back to Shrestha and Timilsina (1996), who used index decomposition analysis (IDA) to quantitatively study the changes of carbon emission intensity in the power industries of Asian countries, including China. They found that fuel intensity was the main factor affecting carbon intensity in China's power industry from 1980 to 1990. Wang et al. (2005) analyzed the changes in China's carbon emissions increase from 1957 to 2000 through the LMDI approach, and pointed out that improving energy intensity was the most important factor for reducing carbon emissions. From the perspective of energy structure and industrial structure, Wu et al. (2005) decomposed the factors of changing energy-related CO_2 emissions and its intensity in China on the basis of the Laspeyres index decomposition model. Huang (2016) revealed that from 2000 to 2012, the proportion of the non-agricultural population, Engel's coefficient and the proportion of the population employed in the secondary industry had positive impacts on China's carbon emissions, while population scale and population aging reduced carbon emissions. However, while Wang and Zhou's empirical analysis showed a non-linear relationship between population structure and carbon emissions, they did not think that a larger proportion of the working age population in the total population led to slower growth of carbon emissions (Wang and Zhou, 2012). Song and Lu (2009) decomposed the relevant factors of CO_2 emission from primary energy consumption at the national level using the "two-stage" LMDI model at different stages. Yu and Kong (2017) studied the factors driving China's carbon emission growth, and their contributions, by introducing the indicators of energy trade during the period of 2000–2014. Using 18 different energy sources during 1991–2015, Liang et al. (2019) adopted LMDI and Tapio decoupling models to study the dynamic evolution of the characteristics and factors influencing industrial carbon emissions in China. All the results listed above identified rapid economic growth as the most important driver for China's carbon emissions increments, while energy intensity and structure and technological progress were the main factors restraining carbon emissions.

In addition, some studies of the factors impacting carbon emissions at the regional, provincial and even city levels have been carried out. Deng et al. (2014) used the LMDI method to disassemble the driving factors of carbon emissions in China's Eight Economic Zones from 1995 to 2010. That analysis showed that the positive effect of economic activity on carbon emissions in developed areas was weaker than in other areas, and the effect of energy intensity had a strong resistance to carbon emissions in areas with active economic restructuring. Wang et al. (2014, 2015, 2017) and Liu et al. (2014) applied the LMDI method to disentangle the changes of carbon emissions in Shandong, Xinjiang, Guangdong and Xiamen City, and the decomposition results showed that economic growth was the most important factor driving the carbon emissions increase, while energy efficiency was the most prominent factor driving the decrease of energy-related carbon emission.

While these studies on the factors driving carbon emissions have undoubtedly achieved numerous meaningful results at different research scales (country, province and city) and provided many effective policy measures, there are still some deficiencies to be improved. First, there are few comparative studies on the carbon emission drivers of typical provinces in the eastern, central and western regions of China (Liu et al., 2010). Second, the existing studies mainly decomposed carbon emissions into economic development, energy intensity, energy structure, and industrial structure, etc., while the demographic structure and residential energy consumption are rarely considered (Ang and Wang, 2015). With the improvement of living standards and the change of lifestyle, the demographic structure (namely, the urbanization and rural population proportions) and residential energy consumption may have important influences on provincial carbon emissions (Geng et al., 2011). Thus, it is essential to reveal the roles of demographic structure and resident energy consumption in provincial carbon emissions.

In this study, we want to address two main questions. First: What are the traits of carbon emission changes in the different provinces and development stages? Second: What are the main factors driving carbon emissions among the different provinces and economic periods, and how do they lead to carbon emissions? These two questions are important for making reasonably targeted emission reductions and environmental protection policies in the eastern, central and western regions of China. To this end, the extended LMDI approach was used to decompose the changing carbon emissions in each economic stage. In light of the research cited above, our work mainly offers the following three contributions. Firstly, we compared the differences in the factors affecting carbon emissions among typical provinces located in the eastern, middle and western areas of China, and obtained helpful conclusions. Secondly, the effects of demographic structure and resident energy consumption within the relationship between energy-related emissions and various driving factors were tested. Thirdly, we extended the data to consider the years 1996–2017, which was very important for capturing the latest developments in provincial energy consumption and economic growth.

2 Research methods

2.1 Selection of typical provinces

We choose the three typical provinces of Jiangsu, Henan and Inner Mongolia, respectively representing eastern, central and western China, to analyse the changes and factors driving carbon emissions from 1996 to 2017. The main reasons for choosing these three provinces are as follows. Firstly, Jiangsu, Henan and Inner Mongolia presented large absolute increments in carbon emissions, which respectively contributed 5.93%, 5.69% and 6.92% of the overall national growth during the period of 1996–2017. Therefore, these provinces should be regarded as the key regions for national emissions abatement. Secondly, these three provinces have obvious regional differences in economic development, technological progress, population scale, resource endowment and industrial structure. At the same time, these differences are also reflected in carbon emissions coming from energy consumption. Specifically, Jiangsu is one of the most developed provinces in eastern China, in which GDP increased from 565.4 billion Yuan in 1996 to 54164.0 billion Yuan in 2017. Its industrial structure, energy consumption (energy mainly coming from external inputs) and technological progress are typical of the eastern region, especially residential consumption which has shown increasing impacts on driving up provincial emissions. Henan is located in the hinterland of China, with a relatively developed economy. The rapid economic development of Henan has played a decisive role in the rise of the central region and the transfer of industries from the eastern coastal areas to the western regions (He and Zhang, 2018). Inner Mongolia is a resource-based province, whose economic growth relies heavily on high energy-consuming industries. Total energy consumption of Inner Mongolia has increased from 16.22 million tons of coal equivalent (tce) in 1996 to 78.56 million tons of coal equivalents (tce) in 2017. Its energy consumption structure and traditional energy industry are representative of the western region (Dong et al., 2016). Therefore, these three provinces may serve as good representatives for studying the factors influencing carbon emissions in detail.

2.2 Data sources

The sample data spanned the period from 1996 to 2017. Provincial carbon emission was calculated according to the final energy consumption data. The data on total population, urbanization level, proportion of the rural population, and GDP were collected from the China Statistical Yearbook (1997–2018), published by the National Bureau of Statistics of China. The final energy consumption data of eight primary types of fossil energy sources (Table 1) for both urban and rural residential energy consumption were obtained from the China Energy Statistical Yearbook (1997–2018), and measured in standard coal equivalents. To eliminate the impact of price fluctuations, the GDP values used in our study were all converted into the 2000 constant prices by using the price index. The energy intensity was the value of energy consumption divided by GDP, and the energy structure was the share of coal consumption in total primary energy consumption. Urban (rural) per-capita energy consumption was the value of urban (rural) residential energy consumption divided by the urban (rural) population.

2.3 Estimation of provincial carbon emissions

As China has no statistical data for CO_2 emissions directly, most studies are based on the indirect calculation based on primary energy consumption. In this study, provincial energy-related carbon emissions were calculated using the final energy consumption according to the IPCC (Intergovernmental Panel on Climate Change) Guidelines for National Greenhouse Gas Inventories. We assumed that all carbon in the fuel was completely combusted and transformed into carbon dioxide, and this study did not take into account the indirect CO_2 emissions discharged by thermal power and heating supply. The calculation formula is as follows:

$$C = \sum_{i=1}^{n} E_i \times e_i \times p_i \times \frac{44}{12} \tag{1}$$

In this formula, C represents total CO_2 emissions from fossil energy consumption ($\times 10^4$ t); i represents the type of energy consumption; E_i represents the total amount of terminal consumption for i type fossil energy ($\times 10^4$ t); e_i is the coefficient of standard coal for i type energy; p_i is the coefficient of carbon emissions for i type energy; 44/12 indicates the mass conversion coefficient from carbon to carbon dioxide; and n represents the number of energy sources. The calculation coefficients of carbon emissions from the eight fossil energy sources are shown in Table 1.

Table 1 Coefficients of the eight fossil energy resources used in carbon emission calculations

Coefficients	Raw coal	Coke	Crude oil	Gasoline	Kerosene	Diesel oil	Fuel oil	Natural gas
e_i	0.7143	0.9714	1.4286	1.4714	1.4714	1.4571	1.4286	13.300
p_i	0.7559	0.8550	0.5857	0.5538	0.5714	0.5921	0.6185	0.4483

Note: e_i and p_i are standard coal coefficient and carbon emission coefficient, respectively, which were derived from the China's Sustainable Development Strategy Report in 2009.

2.4 Decomposition model of provincial carbon emissions

Researchers have developed many methods for quantifying the effects of various factors that contribute to the changes in carbon emissions. Since it is difficult to determine which one is "the best", this study uses the LMDI method without a residual value based on the Kaya identity to quantitatively analyze the effects of various factors on changes of provincial carbon emissions from energy consumption (Baležentis et al., 2011; Song et al., 2015; Wang and Feng, 2018). The Kaya identity usually connects carbon emissions with population scale, economic activity and energy intensity (Kaya, 1989). To quantify the impacts of residential energy consumption and urban-rural population structure on carbon emissions, we extended the identity equation as follows:

$$C = \sum_{i=1}^{2} \frac{C_i}{E_i} \times \frac{E_i}{P_i} \times \frac{P_i}{P} \times P + \frac{C_3}{E_3} \times \frac{E_3}{G} \times \frac{G}{P} \times P \tag{2}$$

where C has the same definition as in Equation (1); C_i represents carbon emissions from urban residential energy consumption (i=1), rural residential energy consumption (i=2) and energy consumption of three strata of industry (i=3); E_i represents energy consumption from urban residents (i=1), rural residents (i=2) and three strata of industry (i=3); P is the total population and P_i denotes urban population (i=1) and rural population (i=2); and G represents the provincial GDP.

Assuming that the change of energy-related carbon emissions from the base year (expressed as 0) to the t year was ΔC_T, then from Equation (2), the ΔC_T can be further decomposed as:

$$\begin{aligned}\Delta C_T &= C_t - C_0 = \Delta C_{PS} + \Delta C_{EG} + \Delta C_{EI} + \Delta C_{ES} + \\ &\Delta C_{UL} + \Delta C_{RPR} + \Delta C_{UPEC} + \Delta C_{RPEC}\end{aligned} \tag{3}$$

where ΔC_T represents the total change of carbon emissions between a base year 0 and a target year t; ΔC_{PS}, the population size effect; ΔC_{EG}, the economic growth effect; ΔC_{EI}, the effect of energy intensity; ΔC_{ES}, the energy structure effect; ΔC_{UL}, the urbanization level effect; ΔC_{RPR}, the effect of rural population ratio; ΔC_{UPEC}, the effect of urban per-capita energy consumption; and ΔC_{RPEC}, the effect of rural per-capita energy consumption. The effect of each influencing factor can be calculated by:

Population size effect:

$$\Delta C_{PS} = \sum_{i=1}^{2} \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \times \ln \frac{P_i^t}{P_i^0} \tag{4}$$

Economic growth effect:

$$\Delta C_{EG} = \frac{C_3^t - C_3^0}{\ln C_3^t - \ln C_3^0} \times \ln \frac{g^t}{g^0} \tag{5}$$

Energy intensity effect:

$$\Delta \boldsymbol{C}_{\boldsymbol{EI}} = \frac{C_3^t - C_3^0}{\ln C_3^t - \ln C_3^0} \times \ln \frac{e^t}{e^0} \tag{6}$$

Energy structure effect:

$$\Delta C_{ES} = \sum_{i=1}^{3} \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \times \ln \frac{f_i^t}{f_i^0} \tag{7}$$

Urbanization level effect:

$$\Delta C_{UL} = \frac{C_1^t - C_1^0}{\ln C_1^t - \ln C_1^0} \times \ln \frac{u^t}{u^0} \quad (8)$$

Rural population ratio effect:

$$\Delta C_{RPR} = \frac{C_2^t - C_2^0}{\ln C_2^t - \ln C_2^0} \times \ln \frac{r^t}{r^0} \quad (9)$$

Urban per-capita energy consumption effect:

$$\Delta C_{UPEC} = \frac{C_1^t - C_1^0}{\ln C_1^t - \ln C_1^0} \times \ln \frac{h_1^t}{h_1^0} \quad (10)$$

Rural per-capita energy consumption effect:

$$\Delta C_{RPEC} = \frac{C_2^t - C_2^0}{\ln C_2^t - \ln C_2^0} \times \ln \frac{h_2^t}{h_2^0} \quad (11)$$

In the above equations, c, p and subscript i have the same definitions as in Equation (2); g represents the per-capita GDP, e represents the energy intensity, f represents the ratio of different fossil energy sources in the total energy consumption, u represents urbanization level, r denotes the ratio of rural population to total population, h denotes the per capita energy consumption; the numbers 1, 2 and 3 represent urban, rural and three strata of industry, respectively; superscript t denotes the end of the period; and superscript 0, the start of the period.

3 Results and analysis

3.1 Characteristics of provincial carbon emissions

As indicated in Fig. 1, fossil energy-related carbon emissions from Henan, Jiangsu and Inner Mongolia all witnessed uptrends, with increases of 102.87 million tons (Mt), 181.89 Mt and 153.36 Mt, respectively, over the entire period of 1996–2017. However, the changes of carbon emissions among the three provinces showed obvious discrepancies in different periods. During the 9th Five-Year Plan period (1996–2000), carbon emissions saw slight increases in Henan and Inner Mongolia, in Jiangsu Province, there was negative carbon emissions growth. That difference may be explained by the following two aspects. First, China's industrialization level was relatively low in this period, and its economic development mainly relied on light industry and labor-intensive industries, causing the growth of provincial fossil energy consumption to be slow, thereby affecting carbon emissions. According to our calculations, the energy consumption in Henan Province increased from 36.24 Mt in 1996 to 36.97 Mt in 2000, corresponding to only a 2.01% increase (Fig. 2a). Second, due to the impacts of the Asian financial crisis in 1997 and national macro-control policies (e.g., in 1996, the State Council promulgated a regulation on shutting down industrial projects with high energy consumption, high pollution and low efficiency), domestic economic growth dropped off remarkably during this stage. As a result, annual average growth rates of per-capita GDP in Henan, Jiangsu and Inner Mongolia were only 8.18%, 9.36% and 8.72%, respectively, which led the annual growth of energy consumption slowing down or even experiencing negative growth (Fig. 2), and thereby controlling the carbon emissions. For example, total energy consumption in Jiangsu decreased from 39.69 Mt in 1996 to 35.34 Mt in 2000, with a corresponding emission reduction of 16.41 Mt. In contrast, during the 10th Five-Year Plan and the 11th Five-Year Plan (2001–2010), the carbon emissions in the above-mentioned three provinces experienced rapid growth; annual growth rates for Henan, Jiangsu and Inner Mongolia were 13.71%, 17.42% and 20.93%, respectively. One reason was that since 2001, China has entered into an accelerated industrialization phase, and simultaneously, China joined the World Trade Organization during the 10th Five-Year Plan period. The acceleration of industrialization and the increase of foreign trade investment had promoted the steady growth of the economy and energy consumption of these three provinces (Fig. 2 and Fig. 3), and thus carbon emissions during 2001–2010. Another reason was that during the period of the 11th Five-Year Plan, the "Four Trillion Yuan Stimulus Plan" enabled China's continuing economic development, despite the influence of the American subprime mortgage crisis in 2008 (Zhao et al., 2014). Accordingly, the aforementioned provinces during this period continued to maintain the relatively rapid economic growth and energy consumption (Wang and Feng, 2018). Especially during this period, the per capita GDP of Jiangsu Province grew by 11.93% and fossil energy consumption increased by 6.42% annually. During the 12th Five-Year Plan (2011–2015) and early stages of the 13th Five-Year Plan (2016–2017), among the three provinces, Jiangsu displayed an initially descending and then rising tendency in carbon emissions, while the other two provinces, Henan and Inner Mongolia, showed fluctuating and decreasing trends. From these results, we found that the three provinces showed carbon emissions changes that were completely consistent with their patterns of energy consumption changes (Fig. 1 and Fig. 2), indicating again that the carbon emissions mainly resulted from fossil energy consumption.

From the view of carbon emissions composition, the three strata of industry (agriculture, commerce and service industry) was the decisive contributor to total carbon emissions. The carbon emission of the three strata of industry accounted for more than 75% of the total carbon emissions in each province. The proportion of carbon emissions caused by residential consumption in the three provinces was relatively small. Among them, the proportion of residents' consumption carbon emissions in Henan decreased the most; while in Jiangsu Province it increased significantly, and in Inner Mongolia it fluctuated greatly (Fig. 1).

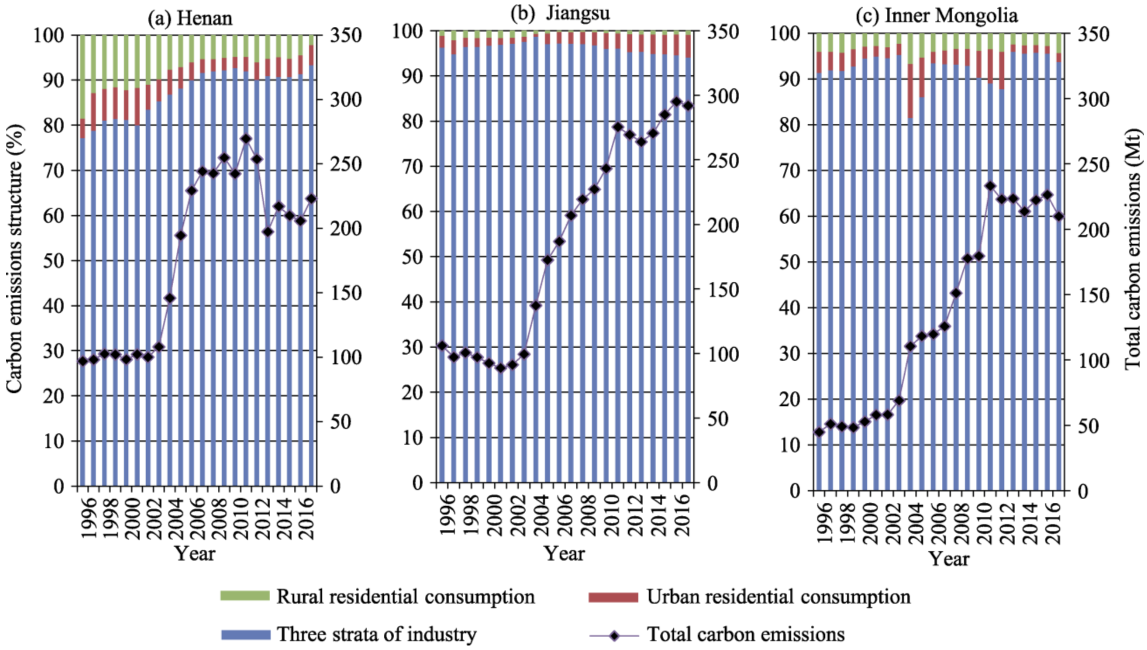

Fig. 1 Carbon emission characteristics of Henan, Jiangsu and Inner Mongolia from 1996 to 2017

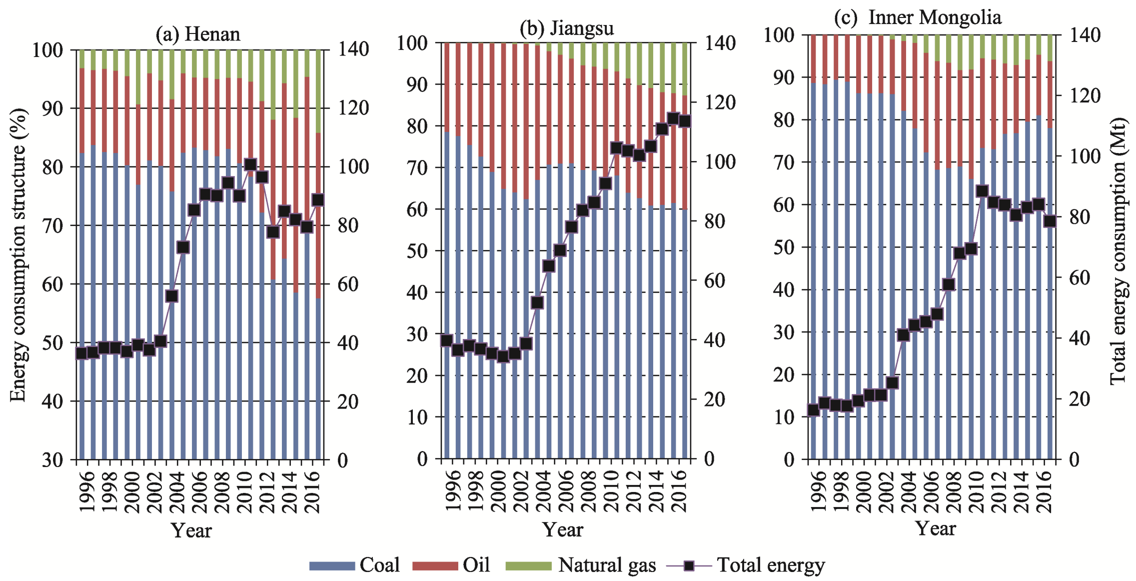

Fig. 2 Characteristics of energy consumption in Henan, Jiangsu and Inner Mongolia from 1996 to 2017

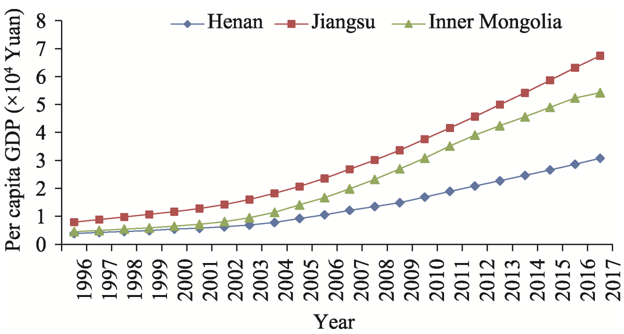

Fig. 3 Changes of per capita GDP in Henan, Jiangsu and Inner Mongolia during the period of 1996–2017

3.2 Overall decomposition of provincial carbon emissions during the entire period

Table 2 and Fig. 4, respectively, present the cumulative effects and the relative contributions of various factors to the growth of provincial carbon emissions. The total growth in carbon emissions (ΔC_T) in Henan, Jiangsu and Inner Mongolia displayed varying degrees of increase, and the roles of the main factors driving the changes of carbon emissions were also quite different in the three provinces. Within the entire period of 1996–2017, the contribution of economic development to emissions growth in Henan, Jiangsu and

Inner Mongolia were respectively 307.19%, 205.08% and 161.26%, indicating that the economic growth effect (ΔC_{EG}) was the primary factor in promoting the increase of the three provinces' carbon emissions. This result may be explained by two factors. On the one hand, growth in economic output usually leads to an increase in fossil energy consumption (Wang et al., 2017; Yu and Kong, 2017; Wang and Feng, 2018). As carbon emission mainly comes from fossil fuel combustion, it can be said that economic development stimulates the increase of carbon emissions. On the other hand, since 2001, China has entered into an accelerated industrialization stage, and needs to vigorously develop the economy to promote the people's material life. Owing to the large proportion of the secondary industry in China, the economic growth driven by rapid industrialization mainly depends on a large amount of fossil energy consumption, resulting in high carbon emissions. Table 2 demonstrates that the cumulative effects of economic growth obviously varied among the provinces. Economic growth in Jiangsu yielded the greatest increment of carbon emissions, while that in Inner Mongolia produced the least, and Henan's increment was between the two. These differences may be attributed to the huge disparities in economic outputs and economic growth rates among the three provinces. In accordance with our calculations, the GDP increments of Henan, Jiangsu and Inner Mongolia were respectively 2586.92 billion Yuan, 4851.05 billion Yuan and 1267.36 billion Yuan from 1996 to 2017, with the largest annual growth rate of GDP found in Jiangsu Province (Table 3). Hence, we can conclude that the stimulating effect of economic growth on carbon emissions may have a similar trend with the economic growth.

Table 2 Cumulative decomposition results of various factors in the three provinces during 1996–2017 (unit: $\times 10^6$ t)

Provinces	ΔC_T	ΔC_{EG}	ΔC_{ES}	ΔC_{EI}	ΔC_{PS}	ΔC_{UL}	ΔC_{RPR}	ΔC_{UPEC}	ΔC_{RPEC}
Henan	102.87	270.03	–9.76	–158.80	4.62	6.74	–4.93	0.14	–5.17
Jiangsu	181.89	373.04	–5.92	–210.89	6.17	6.60	–1.51	6.94	7.46
Inner Mongolia	153.36	246.98	–4.04	–99.35	0.10	1.40	–2.19	1.15	9.31

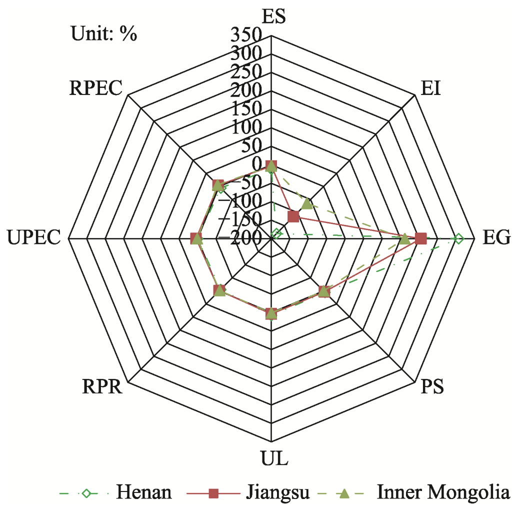

Fig. 4 Contribution rates of various factors to provincial carbon emissions during the period of 1996–2017

Note: The contribution ratio is expressed as the ratio of each of the various effects to the total change of carbon emissions. The same applies to Fig. 5 below.

Energy intensity is an important indicator that reflects the level of energy consumption and energy use efficiency. Table 2 shows that the energy intensity effect (ΔC_{EI}) was the most prominent factor in curbing emissions growth in the three provinces, which was similar to the findings from Wang and Feng (2018). This result may due to the decrease of energy intensity during the whole period examined. As shown in Fig. 5, the energy intensities of Henan, Jiangsu and Inner Mongolia experienced downward fluctuating trends on the whole. Among the three provinces, Inner Mongolia exhibited a larger energy intensity, while Henan and Jiangsu had smaller energy intensities between 1996 and 2017. It is generally true that a lower energy intensity value indicates less energy consumed, and therefore less carbon released. As a result, energy intensity in Jiangsu and Henan had larger restraining effects on their carbon emission increases than in Inner Mongolia during this period (Table 2), and this could be verified by their different contribution rates to emission reductions (Fig. 4). Similarly, the energy structure effect (ΔC_{ES}) also had negative influences on carbon emissions of the three provinces in 1996–2017,

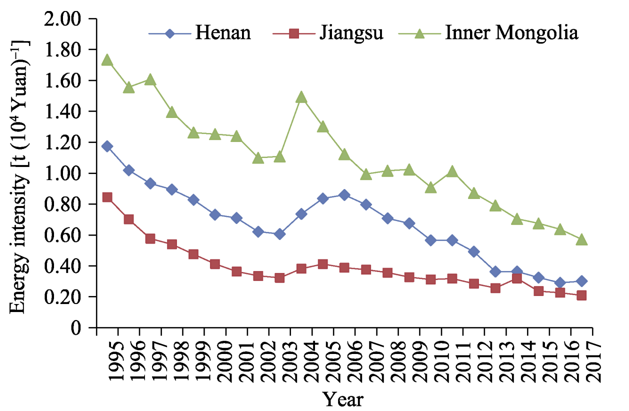

Fig. 5 Energy intensity changes in Henan, Jiangsu and Inner Mongolia during the period of 1996–2017

leading to emission reductions of 9.76 Mt, 5.92 Mt and 4.04 Mt in Henan, Jiangsu and Inner Mongolia, respectively (Table 2). However, compared with the main inhibiting factor such as energy intensity, energy structure change did not exert a significant inhibitory role in carbon emissions over the years, and its contribution rates to emission reductions in the three provinces were very small (Fig. 4). This result may be related to smaller adjustments of the energy structures of three provinces during 1996–2017. Energy structure adjustment refers to the energy substitution between a low-carbon energy type and a high-carbon energy type. As can be seen from Fig. 2, although the proportions of coal consumption in Henan, Jiangsu and Inner Mongolia decreased by 24.86%, 18.63% and 10.62%, respectively, from 1996 to 2017, the overall energy structures of the three provinces did not have significant changes due to the impacts of the energy policies and macroeconomic situations during the period examined. This is especially true in Inner Mongolia, where coal still accounted for nearly 80% of the total energy consumption, which may be due to the coal-dominant energy endowment and economic growth pattern driven predominantly by energy industries in Inner Mongolia (Shao et al., 2016). Thus, effective policies and active measures should be taken to increase the utilization of renewable energy, thereby reducing the reliance on coal.

Table 3 Statistical indicators related to carbon emissions in the three provinces during the period of 1996–2017 (unit: %)

Provinces	PGR	AGGR	ACREI	AUGR	GRRPR	AGRUPEC	AGRRPEC	AGRCC
Henan	18.33	34.66	–3.35	8.23	–38.93	0.10	–1.92	–1.45
Jiangsu	12.92	40.86	–3.34	7.22	–57.02	7.81	26.08	–1.13
Inner Mongolia	9.64	26.98	–3.01	2.92	–38.28	2.29	32.35	–0.57

Notes: PGR—population growth rate; AGGR—annual GDP growth rate; ACREI—annual change rate of energy intensity; AUGR—annual urbanization growth rate; GRRPR—growth rate of rural population ratio; AGRUPEC—annual growth rate of urban per-capita energy consumption; AGRRPEC—annual growth rate of rural per-capita energy consumption; AGRCC—annual growth rate of coal consumption. The same apply to Table 5 below.

In addition, population size effect (ΔC_{PS}), urbanization effect (ΔC_{UL}) and urban per-capita energy consumption effect (ΔC_{UPEC}) also exerted different positive roles in emissions growth in the three provinces between 1996 and 2017 (Table 2). Compared with the economic growth effect, however, their contribution rates were all obviously smaller (Fig. 4). More specifically, population scale played the largest role in promoting carbon emissions in Jiangsu, increasing carbon emissions by 6.17 Mt, followed by Henan and Inner Mongolia. The positive effect caused by urban per-capita energy consumption was also largest in Jiangsu, with 6.94 Mt of growth in carbon emissions, followed by Inner Mongolia and Henan. With regard to the urbanization effect, Henan and Jiangsu displayed increases that were relatively large in carbon emissions compared to Inner Mongolia. The results above may be attributed to the varying degrees of total population, urbanization level and urban per-capita energy consumption in the three investigated provinces (Table 3). For example, based on our calculations, during the whole study period, the annual urbanization rates of Henan and Jiangsu increased by 8.23% and 7.22%, respectively; while that of Inner Mongolia only increased by 2.93%. Comparing the positive effects of population, urbanization and urban per-capita energy consumption in the three provinces, we found that the first two were also the main factors promoting emissions growth. Although urban per-capita energy consumption played a positive role in carbon emissions growth, it was the weakest in the two provinces other than Jiangsu. Therefore, for the provinces with high emissions due to the expanding population scale and the rapid urbanization, appropriately controlling the population scale and actively promoting the process of low-carbon urbanization are expected to have larger effects on abating provincial carbon emissions.

The rural population ratio effect (ΔC_{RPR}) was the third factor inhibiting emissions growth, after the energy intensity and energy structure, in the three provinces during the 1996–2017 period (Table 2), demonstrating that the declining rural population ratio was conducive to the emissions reduction (Fig. 4). However, obvious gaps also existed in the emissions reductions caused by decreases in the rural population proportions across three provinces. As shown in Table 2, in Henan it had the largest impeding effect on carbon emissions, while in Jiangsu it had the lowest inhibitory role in emissions, being far below the level of Henan. The major reason was that, in addition to the discrepancy between provincial rural population levels, provincial rural residential carbon emissions were also affected by some other factors, such as energy supply and consumption patterns, production activity, living environment and lifestyle. As for the effect of rural per-capita energy consumption (ΔC_{RPEC}), Table 2 and Fig. 4 show that ΔC_{RPEC} contributed to emissions reduction in Henan Province, while it contributed to emissions increases in Jiangsu and Inner Mongolia. The reason for this effect was that the rural per-capita energy consumption in Henan decreased, while those in Jiangsu and Inner Mongolia increased. According to our calculations, between 1996 and 2017, the annual growth rate of rural per-capita energy consumption in Henan decreased by 1.92%, while those in Jiangsu and Inner Mongolia increased by 26.08% and 32.35%, respectively (Table 3). Therefore, for provinces with poor carbon performance and high rural per-capita energy consumption, it is imperative to promote low-carbon consumption patterns and lifestyles.

3.3 Decomposition of provincial carbon emissions at different stages

Considering the distinct discrepancies in different periods, we further decomposed the influences of various factors driving the changes of provincial carbon emissions and analyzed the reasons behind the decomposition results in the different economic stages. Table 4 demonstrates the decomposition results of the three provinces' carbon emissions in the different Five-Year Plan periods.

As shown in Table 4, during the 9th Five-Year Plan (1996–2000), the carbon emissions of Henan and Inner Mongolia increased slightly, and in Jiangsu there was a negative growth of 16.41 Mt. The major reason for these trends is that owing to the impacts of the Asian financial crisis, macroeconomic policy regulation and three consecutive years of deflation (Xu et al., 2017), during this stage the sharp decline of domestic investment led to a slowdown of economic growth. Moreover, there was a large decrease in the energy intensity of Henan and Inner Mongolia (Table 5), which to some extent offset the increase of carbon emissions brought by the economic development effect. With regard to Jiangsu, in addition to the financial crisis and macroeconomic policy regulation mentioned above, another important reason lies in other inhibitory factors, such as the energy intensity decline, energy structure adjustment, urban per-capita energy consumption decline, and rural population ratio change, which substantially exceeded the promoting effects from the economic growth, urbanization development, population expansion and rural per-capita energy consumption increase (Table 4). Comparing these eight driving factors, we observed that economic growth was the decisive contributor in the emissions increases in the three provinces, followed by urbanization and population size; while energy intensity had the greatest negative effect on carbon emissions increases, followed by the energy structure and rural population proportion (Table 4, Fig. 6). In addition, residential per-capita energy consumption had differential effects across the provinces. For instance, urban per-capita energy consumption increased carbon emissions in Henan Province, while it reduced emissions in Jiangsu and Inner Mongolia (Table 4). The influencing directions here may depend on the changing directions of urban and rural per-capita energy consumption in the different provinces (Table 5).

Unlike the 9th Five-Year Plan, during the 10th Five-Year Plan (2001–2005), the three provinces experienced the greatest carbon emissions growth among the five stages. Especially in Jiangsu Province, where the growth in carbon emissions increased from –16.41 Mt in the 9th Five-Year Plan to 83.50 Mt in the tenth Five-Year Plan (Table 4). This dramatic change may be attributed to the following three reasons. First, since 2001, China has entered a stage of accelerating industrialization, which has promoted remarkable economic growth and energy consumption, and therefore carbon emissions. Especially in this period, Jiangsu's economic output and population both underwent rapid growth (Table 5), which substantially drove up provincial emissions. Second, China joined the World Trade Organization during this period, and the provincial export-oriented economy developed rapidly, especially in Jiangsu Province in China's eastern region. In addition, China implemented the strategies of western development and central rise, resulting in an improved domestic investment environment and accelerated investment growth. Although the relative contribution rate of economic growth was significantly lower here than in the other periods (Fig. 6), the rapid growth of GDP made economic growth remain as the primary factor stimulating emissions increases. In 2001–2005, the carbon emissions of each province increased by more than 51 Mt. Third, in the previous stage (the 9th Five-Year Plan), energy intensity was the most prominent curbing factor, which showed an active effect on emissions reduction in the three provinces. However, in the 10th Five-Year Plan, energy intensity became the second largest contributor to accelerating emissions growth, and thus had a prominent positive effect on carbon emissions. The increase of energy consumption intensity in this period may explain why energy intensity exerted such a strong promoting effect in the 10th Five-Year Plan. As indicated in Fig. 5, the three provinces' energy intensities maintained a steady downward trend over the entire period, but had varying degrees of increase during 2003–2005 as the proportion of secondary industry in the three provinces increased greatly and the production of high energy consuming products increased (e.g., the proportion of secondary industry in Jiangsu increased 3.14% compared to the 9th Five-Year Plan), which meant that producing a unit of industrial output consumed more energy. Furthermore, the increases of carbon emissions may be related to the effect of energy structure conversion in the different provinces. We found that in the three provinces, the influence of energy structure on carbon emissions changed from a negative effect in the 9th Five-Year Plan to a positive effect in the 10th Five-Year Plan, which may be mainly due to the increasing proportion of coal consumption in the total energy consumption (Table 5) and coal consumption usually has relatively high carbon emissions. Similar to the energy structure, the effect of conversion resulted from residential per-capita energy consumption occurred in Jiangsu and Inner Mongolia. The above reasons ultimately led the large increases in carbon emissions of the three provinces. As for other effects, such as population size effect, urbanization level effect and rural population ratio effect, they did not have obvious changes in this period compared with the 9th Five-Year Plan.

During the 11th Five-Year Plan (2006–2010), Jiangsu and Inner Mongolia still witnessed the larger growth in carbon emissions, while Henan had an inconspicuous emission growth, and the economic growth remained the largest of the driving factors (Table 4). For example, although the total net growth of carbon emissions in Henan Province was only 6.76 Mt, the economic growth resulted in about 101.0 Mt of carbon emissions growth, which contributed more than 1495% to the total net increase in carbon emissions (Fig. 6a) because this stage was a period of rapid economic development. Despite the impact of the subprime mortgage crisis in 2008, the economies of the provinces of Henan, Jiangsu and Inner Mongolia continued to develop rapidly due to the national "Four Trillion Yuan Stimulus Plan" (Table 5). Meanwhile, their economic growth still mainly depended on high energy-consuming secondary industries, so the overall energy consumption was high, thus causing a large increase in carbon emissions. Moreover, while the population size effect and urbanization effect also played active roles in three provinces' emissions increments, their contributions to carbon emissions were not significant (Fig. 6). For instance, the contribution ratios of population size and urbanization in Jiangsu and Inner Mongolia only ranged from 0.3% to 2.0%, indicating that the effects of population size and urbanization on driving emissions growth were very weak.

Table 4 Decomposition results of various factors affecting carbon emissions in the three provinces during different periods

(unit: $\times 10^6$ t)

Periods	Provinces	ΔC_T	ΔC_{EG}	ΔC_{ES}	ΔC_{EI}	ΔC_{PS}	ΔC_{UL}	ΔC_{RPR}	ΔC_{UPEC}	ΔC_{RPEC}
The 9th Five-Year (1996–2000)	Henan	2.71	26.48	–0.42	–25.65	1.00	1.22	–0.90	0.83	0.15
	Jiangsu	–16.41	36.73	–2.04	–50.73	0.74	0.91	–0.27	–2.22	0.47
	Inner Mongolia	5.02	16.33	–0.58	–9.84	0.15	0.16	–0.12	–0.89	–0.19
The 10th Five-Year (2001–2005)	Henan	78.40	57.30	2.75	19.78	0.34	0.41	–1.11	–2.99	1.92
	Jiangsu	83.50	58.67	3.71	15.34	1.37	2.00	–0.18	2.80	–0.21
	Inner Mongolia	70.84	51.52	2.18	3.76	0.20	0.36	–0.23	8.31	4.75
The 11th Five-Year (2006–2010)	Henan	6.76	101.11	–0.30	–89.64	1.27	1.30	–1.20	–3.88	–1.90
	Jiangsu	55.88	96.61	–2.01	–44.83	1.00	1.04	–0.16	3.16	1.07
	Inner Mongolia	61.21	83.06	–2.60	–28.70	0.23	0.79	–0.83	6.51	2.75
The 12th Five-Year (2011–2015)	Henan	–58.55	73.62	–10.03	–121.07	0.63	1.24	–1.33	–1.21	–0.40
	Jiangsu	12.19	91.74	–5.60	–78.64	0.36	0.77	–0.27	2.69	1.14
	Inner Mongolia	–31.51	69.83	–2.31	–85.40	0.14	0.56	–0.61	–12.08	–1.64
Initial stage of the 13th Five-Year (2016–2017)	Henan	14.57	14.31	–6.38	6.88	0.19	0.31	–0.22	2.22	–2.74
	Jiangsu	–2.15	18.22	–0.16	–21.53	0.18	0.21	–0.08	0.73	0.28
	Inner Mongolia	–13.04	7.36	–1.33	–22.04	0.07	0.05	–0.16	0.18	2.83

Table 5 Description of statistical indices related to carbon emissions in the three provinces during different periods (unite: %)

Statistical indicators	The 9th Five-Year (1996–2000)			The 10th Five-Year (2001–2005)			The 11th Five-Year (2006–2010)			The 12th Five-Year (2011–2015)			Initial stage of the 13th Five-Year (2016–2017)		
	Henan	Jiangsu	Inner Mongolia	Henan	Jiangsu	Inner Mongolia	Henan	Jiangsu	Inner Mongolia	Henan	Jiangsu	Inner Mongolia	Henan	Jiangsu	Inner Mongolia
PGR	3.00	3.05	2.85	–1.83	3.12	0.91	0.14	2.79	2.36	0.98	0.98	1.18	0.28	0.38	0.36
AGGR	10.54	12.82	11.93	14.38	24.76	16.67	15.03	16.03	22.23	10.19	10.59	10.36	7.81	7.20	4.00
ACREI	–7.06	–10.29	–4.88	4.43	3.34	1.27	–8.51	–4.88	–4.77	–10.66	–6.37	–8.35	3.54	–7.48	–10.13
AUGR	6.54	12.98	2.43	6.37	4.37	2.10	4.64	4.18	3.54	3.87	1.87	1.62	3.42	1.54	1.36
GRRPR	–5.89	–19.51	–6.07	–8.23	–13.76	–6.49	–8.93	–18.06	–13.42	–10.57	–12.13	–8.48	–3.22	–3.22	–2.14
AGRUPEC	4.25	–15.80	–10.26	–7.21	54.98	139.46	–10.16	15.74	49.46	–3.30	7.15	–18.51	26.81	5.37	4.82
AGRRPEC	0.20	11.79	–2.62	5.21	–3.97	75.26	–1.21	73.03	15.24	–0.52	18.21	–5.31	–33.10	11.44	45.18
AGRCCR	–0.63	–3.05	–0.66	1.77	2.24	2.38	–0.81	–1.24	–2.16	–6.32	–2.62	2.09	–16.65	–2.59	–3.69

One observation calling for special attention is that the energy intensity and energy structure were emissions-growth contributors in the 10th Five-Year Plan, while they became emissions-reduction contributors during this period. The restraining effect of energy intensity and structure may have resulted from their obvious decreases in this stage. In particular, energy intensity became the primary determinant of emission mitigation during the 11th Five-Year Plan. Comparing the energy intensity changes in the three provinces during 2006–2010, we found that the energy intensity in Henan Province had a remarkable decline (Table 5), causing an 89.64 Mt decrease in carbon emissions. This was because in this stage, the industrial restructuring or technological progress of Henan Province had a great flexibility in impacting carbon emissions, and the level of energy efficiency was improved rapidly, which led to a great inhibition of carbon emissions. Correspondingly, the contribution of energy intensity to emissions reduction in Henan was significantly greater than those in the other two provinces (Fig. 6), which made the limiting effect from energy intensity in Henan Province offset the stimulating effect of economic growth on carbon emission to a large extent. This balance could explain why the carbon emissions in Henan Province displayed a slight increase during the 11th Five-Year Plan. Besides, compared to the former two stages, the rural population effects in Henan and Jiangsu did not display obvious changes in this stage (Table 4). However, the inhibitory effect of the rural population ratio in Inner Mongolia clearly strengthened, resulting in 0.83 Mt of emission reduction, which may be due to the dramatic decline of the rural population ratio in Inner Mongolia during this period. From Table 5, the growth rate of the rural population ratio in Inner Mongolia dropped from −6.49% in the 10th Five-Year Plan to −13.42% in the 11th Five-Year Plan. This change was far larger than those coming from the growth rate of the rural population ratio in Henan and Jiangsu. Furthermore, the rural production conditions and living environment in Inner Mongolia are worse than those in Henan and Jiangsu. According to Wu et al. (2005), worse production and living conditions lead to more energy consumption and carbon emissions. As a result, the significant decline of the rural population ratio in Inner Mongolia ultimately led to a remarkable decrease in carbon emissions compared with the other periods. In addition, the reduction of the proportion of the rural population also meant the acceleration of modern agriculture to replace the traditional agriculture with high carbon emissions, thus driving the reduction of rural carbon emissions. Nevertheless, the absolute contribution of the rural population proportion to the total emissions growth was obviously lower than those of the main factors such as economic growth and energy intensity in the three provinces, which was consistent with the conclusions of previous studies (Chen et al., 2019; Zhu et al., 2010). Only in Henan Province did the proportion of rural population contribute over 17% reduction to the total emissions increase (Fig. 6a). Compared to the 10th Five-Year Plan, urban and rural per-capita energy consumption had the same alternative impacts on carbon emissions, except for the differential degrees of influence in the 11th Five-Year Plan. Their influencing directions still depended on the changing directions of urban and rural per-capita energy consumption in these provinces (Table 4).

During the 12th Five-Year Plan (2011–2015), the carbon emissions in Henan and Inner Mongolia declined 58.55 Mt and 31.51 Mt, respectively, which were the smallest growths of carbon emissions in the five Five-Year Plan periods; and simultaneously, Jiangsu's carbon emissions also only increased by a small amount: 12.19 Mt (Table 4). This indicated that, after a prolonged increase, the three provinces' carbon emissions began to decrease sharply, demonstrating that the emissions reduction efforts have produced active results in the three provinces. In this period, economic growth in the three provinces of Henan, Jiangsu and Inner Mongolia slowed significantly due to the global economic recovery and national macroeconomic conditions (Table 5), but economic growth was still the primary promoter in accelerating carbon emissions increases. This factor contributed the greatest positive effects in Jiangsu. It is interesting to note that the contribution of economic development to total carbon emissions of Henan was substantially reduced (Fig. 6), which may due to the relatively low GDP growth in Henan during the 12th Five-Year Plan (Table 5). Moreover, population scale and urbanization had positive effects on the growth of carbon emissions, and the promoting effect resulting from the acceleration of urbanization was larger than that coming from the expansion of population size (Table 4). This means that actively promoting the processes of low-carbon oriented urbanization should be the focus of emission reduction for these provinces.

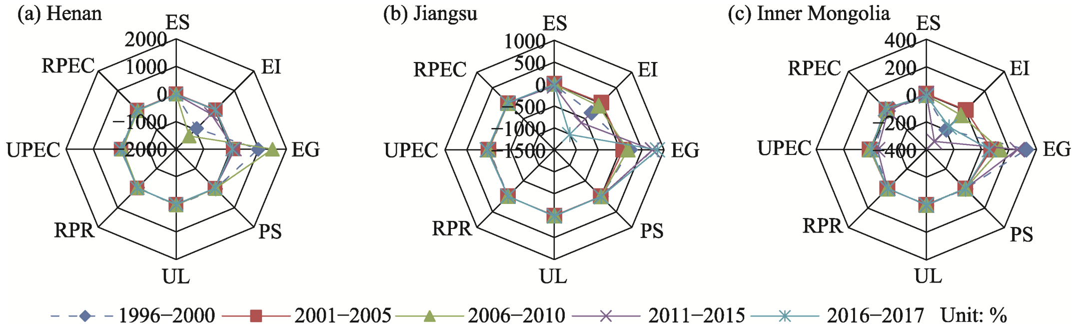

Fig. 6 Contribution rates of various factors to the provincial carbon emissions during different periods

During this period, energy intensity, energy structure and rural population ratio played active roles in emissions reductions. Among them, energy intensity reduction was primarily responsible for the decrease in emissions. However, the inhibiting effects of energy intensity in Jiangsu and Inner Mongolia were obviously less than that in Henan Province (Table 4), which might be attributed the energy intensity differences in the three provinces. Specifically, as Henan has undertaken some late-model industries from the eastern region, and merged and shut down local high energy-consuming enterprises, the energy intensity dropped dramatically and exhibited a prominent curbing effect on emission growth. As for Jiangsu in the eastern region, its industrial restructuring has been accomplished preliminarily during this period; hence the potential for emission reduction from energy intensity was basically exhausted at the current technology level. Inner Mongolia is a coal-rich economy province, with a large proportion of traditional industries and economic dependence on resource-based industries, so the inhibitory effect of energy intensity on carbon emissions was relatively weak. Energy structure was the second major factor curbing carbon emissions growth, and it contributed to the carbon emissions reductions, indicating that the energy structure adjustments of the three provinces gradually tend to be reasonable. In particular, the combined inhibitory effects of energy intensity and energy structural changes had completely offset the stimulatory effects of economic and population expansion in Henan and Inner Mongolia, the result of which was an absolute (net) reduction of provincial carbon emissions during 2011–2015. Besides, although rural and urban per-capita energy consumption still displayed mixed results among the different provinces, these two factors yielded prominent roles in terms of abating emissions in Inner Mongolia (Table 4). This development implied that during this period, the per-capita energy consumption in Inner Mongolia was developing in a direction that was conducive to carbon emission reduction.

During the initial stage of the 13th Five-Year Plan (2016–2017), the two provinces of Henan and Inner Mongolia (but not Jiangsu) witnessed rebounds in total carbon emissions. In particular, Henan experienced a positive growth in carbon emissions (Table 4), which may have two possible reasons. On the one hand, since the beginning of the 13th Five-Year Plan, China's economy has actively adapted to and led the "new normal", showing a steady, positive and progressive trend. Especially in 2017, China's economy achieved a medium-speed growth in the world economic downturn, which led to a rapid increase in carbon emissions in most provinces of China. (Note, however, that the economic growth in Inner Mongolia was relatively slow, leading to small effects in promoting carbon emissions). On the other hand, this may be attributed to the conversion of energy intensity effect. In other words, in the former period, the emissions reductions mainly benefited from a prominent energy intensity effect. However, in this stage, the inhibiting effects coming from energy intensity converted to a promoting effect induced from the energy efficiency decline in Henan. Thus, specific attention should be paid to facilitating the energy efficiency improvement in Henan Province. Moreover, because some energy-intensive industries in the eastern region gradually transferred to the central region, the restraining effect of the energy structure in Henan Province was significantly reduced, compared with the situation during the 12th Five-Year Plan. Meanwhile, the growth of urban per-capita energy consumption also led to an obvious emission increase in Henan Province, although its contribution was relatively small. With regard to the negative growth of carbon emissions in Jiangsu and Inner Mongolia, it may indicate that the curbing effects obtained from the energy intensity decline, energy structure adjustment (coal consumption decline) and rural population decline exceeded the promoting effects coming from the economic development, population scale expansion, acceleration of urbanization, and urban per-capita energy consumption growth. On the whole, in this stage, economic growth was still the primary stimulating factor, causing 18.22 Mt of carbon emissions growth in Jiangsu, but its contributions were substantially reduced in Henan and Inner Mongolia (Table 4, Fig. 6). Energy intensity was the strongest curbing factor, which contributed the most to carbon emissions reduction in the provinces examined, except for Henan. Energy structure change was conducive to emissions reduction in Henan and Inner Mongolia, while it had a marginal effect in Jiangsu (Table 4), and its absolute contribution only accounted for 7.52% of the total in Jiangsu (Fig. 6). The main cause of this small effect may be that Jiangsu is a major energy consumption province in the east of China, and its energy has always been dominated by external inputs. In recent years, the industrial restructuring and energy structure optimization in this province has been completed (Wang and Wang, 2011). In contrast, the other two provinces of Henan and Inner Mongolia were important energy supply bases, and their economic growth levels were mainly driven by large-scale energy industries and the coal chemical industry. Thus, the energy structural adjustment effectively curbed the growth of carbon emissions in Henan and Inner Mongolia. Other factors, such as population size, urbanization and rural population proportion had marginal effects on carbon emissions in the three provinces. Additionally, the impact of rural per-capita energy consumption on carbon emissions still exhibited differential effects in the different provinces (Table 4).

4 Discussion

This paper analyzed and decomposed the changes of energy-related carbon emissions in the three typical provinces of Jiangsu, Henan and Inner Mongolia, respectively located in the eastern, central and western regions of China from

1996 to 2017. Based on the composition of carbon emissions, the three strata of industry was the top contributor to carbon emissions increases. Although the proportions of carbon emissions caused by residential consumption in the three provinces were relatively small, they represented more than 5% of the total emissions of each province, and this proportion had an obvious increase particularly in Jiangsu province. This suggested that the impact of residential consumption on carbon emissions cannot be ignored.

Decomposition results indicated that economic growth was the leading contributor to carbon emission growth in all economic stages, although the extents of promotion were different in various provinces and different economic periods due to the discrepancies between provincial levels of economic development. This is because economic development, along with a large amount of fossil energy consumption, directly led to large amounts of carbon emissions (Kang et al., 2016). Moreover, in order to maintain rapid economic growth and social development, China will inevitably increase the demand and consumption of fossil energy, thus causing increasing carbon emissions to the environment. Therefore, effectively carrying out economic transformation and upgrading is the key to reducing the carbon intensity of economic production of the three provinces in the near future. Comparatively speaking, the economic transformation and upgrading of Jiangsu and Henan in the eastern and central regions has been better than that of Inner Mongolia in the Western Region (Ye et al., 2017). For the developing western provinces, like Inner Mongolia, the economic growth driven by the energy-intensive industries have predominantly made the emissions mitigation goals quite difficult to realize, owing to the high energy intensity and poor carbon performance. It has been proven that technological progress can reduce energy intensity, thus indirectly reducing carbon emissions (Zhang and Da, 2015). Hence, the local government should encourage the introduction and innovation of advanced energy-processing technologies to reduce energy intensity and improve carbon performance in Inner Mongolia. In this study, energy intensity was the most important factor for restraining carbon emissions growth in all economic stages, except during the 10th Five-Year Plan. The decline of energy intensity has greatly mitigated carbon emissions growth of the three provinces. However, although energy intensities of Jiangsu and Henan have achieved great declines during the past years (Fig. 5), they are still higher than the average level of developed countries, and so they have a great potential for reduction with the aim of reducing China's carbon intensity of GDP by 60%–65% (NDRC, 2015). Therefore, the eastern and central provinces, such as Jiangsu and Henan, should persistently extend the effects of their energy intensity declines by technical progress on emissions abatement. Moreover, energy intensity is closely related with industrial structure, thus, efforts should focus on promoting the low-carbon oriented industrial restructuring, increasing the proportion of the third industry and taking a low-carbon development road focusing on high value-added and low energy-intensive options.

Compared with energy intensity, although energy structure was the second major curbing factor and led the mitigation in emissions growths to some extent, it did not exert the full inhibitory effect on carbon emissions because the energy structure adjustment was relative marginal (Meng et al., 2018). Coal remained the primary energy source in the various provinces of China, especially Inner Mongolia. This implies that there is still a lot of room for emission reduction through energy structure optimization. Sun et al. (2018) found that the energy consumption structure had a significant impact on China's regional carbon emissions. On this account, net energy-consumption provinces such as Jiangsu and Henan should persistently expand the diversified allocation of low-carbon oriented energy sources to achieve carbon emissions reduction, and strengthen the demand-side management to restrain the growth of energy demand. Meanwhile, net energy-production provinces like Inner Mongolia should reduce industrial reliance on coal and the proportion of fossil energy consumption, and further promote the generation of renewable energies such as wind, solar, and biomass.

Population size and urbanization were always contributors to carbon emissions growth in the three provinces examined, although their respective contributions were far smaller than that of economic growth. Moreover, we were quite surprised to note that the impact of urbanization on carbon emission outstripped that of population scale. One reason for this phenomenon is that the increase of population size will lead to high population density and intensive energy consumption, and thereby yield a positive effect on carbon emissions. However, with the progress of urbanization, in addition to high population agglomeration and residential energy consumption, large-scale infrastructure construction is needed in the early stage of urbanization, which brings about an increase in energy consumption and therefore more carbon emissions. At present, China is in a stage of rapid urbanization and its energy consumption is still growing, but with the acceleration of new urbanization processes, the improvement of infrastructure and the enhancement of environmental awareness, the impact of urbanization on carbon emissions will be diminished in the mid-late stages of urbanization. In our study, the effect of urbanization on provincial carbon emission growth in the former four stages was greater than that in the final stage. This result is consistent with Ma (2015), who found that carbon emissions will eventually be reduced in the later stage of urbanization. Moreover, the influence of population size on carbon emissions showed a decreasing trend with time, but with some differences across the provinces. However, for the populous province of Henan in the central region, the growth of carbon emissions caused by population size and rapid urbanization cannot be ignored.

The effect of rural population proportion was the weakest among all of the curbing factors, but it was always a contributor to facilitating emission-reduction in all provinces and economic stages. The effects of residential energy consumption per capita on carbon emissions varied across the provinces. For example, in the developed and highly urbanized Jiangsu Province, residential per-capita energy consumption contributed over 7.9% to the total carbon emission growth in the entire period of 1996 to 2017, among which urban residents per-capita energy consumption contributed more than 3.8%. In another instance, during the tenth Five-Year Plan, the highest level of carbon emissions growth caused by residential per-capita energy consumption appeared in the coal-rich Inner Mongolia (Table 4), in which the growth in carbon emissions surpassed 13.0 Mt, accounting for more than 18.4% of the total growth in carbon emissions. Although carbon emissions from per-capita energy consumption and its contributions to the total provincial emissions growth were still relatively low, the per-capita energy consumption in Inner Mongolia and Jiangsu began to play increasingly important roles in driving up carbon emissions growth. This means that the residential consumption is expected to become the emerging engine of provincial carbon emissions increases. Therefore, a variety of measures should be formulated to prevent the possibly large growth of residential carbon emissions that may occur in the mid-late stages of urbanization. Zhang and Lin (2012) pointed out that promoting the low-carbon consumption pattern and lifestyle is one feasible way to reduce residential emissions. Besides, residential per-capita energy consumption displayed two obvious patterns in different provinces and economic stages, and its influencing direction was sensitive. We also found that in the same province, the absolute effect resulting from urban resident's per-capita energy consumption was distinctly greater than that from rural resident's per-capita energy consumption in most economic stages (Table 5). In addition to energy supply and demand, energy efficiency and production technology, the major reason was that the urban per-capita energy consumption was also affected by some other factors, such as urbanization, income per capita, and lifestyle. High energy efficiency in urban areas usually reduces per-capita energy consumption, while the acceleration of urbanization and increase of per-capita disposable income lead to the growth of urban per-capita energy consumption. In the process of urbanization, the transformation of a rural resident into an urban resident will cause an estimated increase of 1085.3 kg standard coal consumption (Zhang et al., 2011). Furthermore, with the improvement of the rural living standard, rural resident's consumption tendency has gradually changed from that of survival consumption to development consumption, leading to the continuous growth of indirect energy consumption in the fields of transportation, communication, education and entertainment, medical and health care, etc. Therefore, the impact of rural per-capita energy consumption on carbon emissions should be paid serious attention in the future.

There can be no doubt that this study has certain limitations. For example, investment intensity and R & D intensity may have important impacts on carbon emissions, however, the relationships of these factors to energy intensity are not tested in the extended LMDI model. Second, the factors affecting carbon emissions are usually highly inter-correlated (Subhes and Wataru, 2010; Tan et al., 2011). In this study, our model assumes that these drivers are independent, thus, with the LMDI approach it is difficult to distinguish the individual impacts of each factor on carbon emissions. Third, this study only uses population urbanization of each province. If the impacts of land urbanization and population urbanization on carbon emissions are considered comprehensively, more interesting conclusions could be obtained on the influences of urbanization on carbon emissions. These enhancements need to be explored in the future.

5 Conclusions

In order to raise the awareness among China's decision makers of the spatial characteristics and factors influencing carbon emissions at the provincial level, this study used an extended LMDI approach to decompose the driving factors of carbon emissions in three typical provinces during the whole study period and different economic stages. Three conclusions were reached herein.

First, the energy-related carbon emissions of the three provinces were on the rise across the whole period, but in different economic stages, the provincial carbon emissions displayed diverse growth characteristics. The three strata of industry was the top contributor to provincial carbon emissions. Carbon emission from residential consumption was relatively small, but accounted for more than 5% of the provincial emissions. In particular, the carbon emissions from residential consumption in Jiangsu showed an increasing trend.

Second, the decomposition results showed that the effects of various factors on carbon emissions varied across provinces. Economic growth was the leading contributor to increasing carbon emissions in the three provinces during all economic stages, followed by urbanization level and population size. In addition, the impacts of urbanization in the earlier four stages were larger than that in the last stage, and the influence of population size on carbon emissions also showed a downward trend over time.

Third, the decline of energy intensity and the adjustment of energy structure both curbed the increases of carbon emissions in three provinces during different economic stages, except for during the 10th Five-Year Plan. The energy intensity exerted a remarkable effect in offsetting provincial emissions growth, followed by energy structure and rural population proportion. The effect of residential per-capita energy consumption on carbon emissions displayed two obvious patterns in different provinces and economic periods, and its influencing direction was sensitive. In a given province, the absolute effect resulting from urban residential per-capita energy consumption was distinctly greater than that from rural residential per-capita energy consumption in most economic stages.

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中国典型省（区）能源消费碳排放比较降解分析——以江苏、河南、内蒙古为例

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摘　要：准确查清典型省份能源消费碳排放的实际情况及其碳排放增长的主要驱动因素，是实现我国碳减排目标的关键。本文采用扩展的 LMDI 模型对来自中国东、中和西部地区三个典型省（区）——江苏、河南和内蒙古的碳排放增长进行了比较分解。结果表明：(1)1996–2017 年，3 个省（区）的能源消费碳排放变化呈上升趋势，但各省（区）之间存在明显差异。(2)各驱动因素对碳排放的影响在不同省份和不同经济发展期明显不同。经济增长对各省碳排放变化的正向贡献最大（1996–2017 年，河南、江苏、内蒙古三省（区）经济发展对碳排放增长的贡献分别为 307.19%、205.08% 和 161.26%）；其次是城镇化和人口规模，但对碳排放增长的贡献远小于经济增长。(3)除“十五”规划期外，能源强度在促进 3 省（区）碳减排方面发挥了主导作用，其次是能源结构。在所有抑制碳排放增长的因素中，农村人口比例的贡献最小。此外，城乡居民人均能源消费对碳排放的影响在不同省份（区）和不同经济发展阶段均表现出相对较小的影响和两面性，但在推动省域碳排放的变化方面开始起着越来越重要的作用（如 1996–2017 年，江苏省的居民能源消费对碳排放增长的贡献率超过 7.9%，其中城镇居民人均能源消费的贡献率大于 3.8%）。鉴于此，建议政策制定者应根据东、中、西部地区的碳排放省情和影响碳排放的关键因素，制定有针对性的减排措施。

关键词：碳排放；降解分析；LMDI 方法；中国典型省份