



# Estimation, decomposition and reduction potential calculation of carbon emissions from urban construction land: evidence from 30 provinces in China during 2000–2018

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## Abstract

With 80% of the world's carbon emissions coming from urban areas and most part of the world still experiencing ever accelerated process of urbanization, China faces huge pressure to achieve the carbon emission peaking in 2030 and realizes the goal of carbon neutrality before 2050. Therefore, this study explored the spatial variability of CO<sub>2</sub> emissions from urban construction land among 30 provinces in China, analyzed its driving factors and estimated their potentials for emission reductions from 2000 to 2018. The results demonstrate that: (1) according to the IPCC model, both the carbon emission amounts and carbon emission intensity from urban construction land showed an upward trend from 2000 to 2018. (2) Decomposition analysis of logarithmic mean Divisia index revealed that economic level has positive impact on carbon emissions. Energy efficiency and energy structure are the negative contribution factors to the carbon emissions, and the energy efficiency effect played a more important inhabiting factor. (3) The carbon emission reduction potential indexes was provided to estimate the carbon emission reduction potential of 30 provinces in China; it indicated that 17 provinces have their carbon emission reduction potential indexes less than 1, and they confront with mandatory push to reduce carbon emission under the current national policy. Finally, promoting clean energy and applying internet of things into energy transport corridor system and more low-carbon land planning policies are suggested to facilitate more effective implementation of carbon emissions reduction actions in China.

**Keywords** Urban construction land · Carbon emissions · Spatiotemporal characteristics · Decomposition analysis · Carbon emission reduction potential

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## 1 Introduction

Climate change caused by carbon emission has induced severe problems to human survival and development, such as extreme climates, ecological fragility and economic losses (Li, 2017; Wang & Zheng, 2012; Zhang & Zhou, 2020). Research shows that land use and cover changes are the second largest cause of the increase in carbon emissions in the atmosphere after the burning of fossil fuels (Stuiver, 1978). Currently 80% of global carbon emissions come from urban areas (namely, the urban-built area), which only accounts for 2.4% of the land area; therefore, the intensity of urban construction land carbon emission is as thousands times as that of agricultural construction land or other land use types (Churkina, 2008; Ghaffar & Vilas, 2012; Qing, 2010; Shan et al., 2017).

After surpassing the USA to become the world's biggest carbon emitter, China has committed to reach the carbon peak before 2030, lowered the carbon dioxide emissions per unit of GDP by more than 65% from the 2005 level and achieved carbon neutrality before 2060 (Lai et al., 2016). China is in the process of unprecedented industrialization and urbanization, which has discharged huge carbon emissions due to the expansion of construction land. The rapid urbanization stage happens to be the key node to achieve carbon emission reduction (LuXia et al., 2016). Against the background trend in China's economic growth and an upward trend in urbanization process, whether and how China can achieve the emission reduction goal and commit its carbon emission reduction promise has been an important issue confronted by the central and local governments to behave as a responsible country (Shen et al., 2018; Tan et al., 2016; Zhao et al., 2013). As local governments gradually replace national ministries and commissions as the main implementer of energy conservation and emission reduction policies, optimization of land use structure has become one of the important tools for realizing regional carbon emission control (Zhao et al., 2013). So, this paper analyzes the temporal and spatial evolution of carbon emissions based on the perspective of land use. Despite that China currently has a large amount of idle construction land in rural areas, urban areas occupying only 2% of the overall land area, however, they account for approximately 75% of the global carbon emissions (Huo et al., 2020a). Moreover, owing to the increasing size of urban construction land, the carbon emission from it takes an obvious advantage in quantity terms and has been widely regarded as the fundamental part for China to reach the carbon reduction targets (Zhu et al., 2018). Therefore, this paper takes urban construction land as the research object to explore the relationship between it and carbon emissions, and optimize the land use structure to achieve carbon emission reduction goals.

Literature associated with urban carbon emissions mainly included the following 3 sections: (1) the estimation of carbon emission amounts from urban construction land. Accurate carbon emissions accounting is the foundation to achieve carbon reduction (Qian et al., 2018). It originally focused on how to define the boundary of urban construction land and enriched by the various research levels (Cubasch & Hu, 2001; Houghton & Hackler, 2001; Houghton et al., 1983), which included the consuming-based perspective research, all upstream and downstream emissions perspective and carbon emissions caused by urban spatial attributes such as buildings, transportation, vegetation, and residence (Chuai et al., 2015; Grimm et al., 2008; Jones & Kammen, 2014; Zhang et al., 2013). However, researches that based the first perspective faced serious estimation error due to the international and inter-provincial trade issue, double counting and residuals handling make the all upstream and downstream emissions perspective model unable to account for all changes in carbon emissions, which are

also threats to the precision of estimation. The IPCC method gradually and widely is accepted by scholars due to its absolute advantages in covering all sectors without double counting (Cubasch & Hu, 2001; Eggleston et al., 2006). Other scholars began to explore changes in carbon emissions from construction land based on different administrative levels (Jing et al., 2018; Wang et al., 2020). (2) The carbon emission decomposition is the key part for policy makers to identify the critical drivers of carbon emission, which is urgently needed for the policymakers to design reduction policies (Oh et al., 2016; Zhang et al., 2020). Therefore, the following studies have showed their passion in the relationship between influencing factors of carbon emissions, and methods widely adopted contain measurement model analysis method (STIRPAT) and factor decomposition analysis methods (Ang & Liu, 2007; Li et al., 2018; Tallarico & Johnson, 2010). However, the two methods cannot handle the residuals which make the model unable to account for all changes in carbon emissions. Ang et al. analyzed and improved the above method and concluded a new type of exponential method that can completely decompose the factors to be decomposed without difference, called logarithmic mean Divisia index (LMDI), which has been widely applied in practical research (Ang & Choi, 1997; Fan & Lei, 2017; Huo et al., 2020b). (3) The analysis of carbon reduction potential in the field of urban construction land plays an fundamental role in the realization of China's carbon reduction commitment as well as achieve the carbon neutrality target, which makes it a hot topic recently (Cai et al., 2021; Shi et al., 2021). Some literature began to explore how to increase the carbon sink while reducing the carbon emission (Li et al., 2020). Shao et al. (Shao et al., 2018) show that the increase in urban greening, expansion of wetlands in urban rivers and lakes, and use of rainwater resources lead to carbon reduction effects in the city, which was restricted by the limited land. Some scholars pay their attention to methods that account for the carbon reduction potential estimation involved in the scenario analysis (Li et al., 2021) and field-based experiments (Yao et al., 2020). However, the uncertainty brought by scenario analysis always leads to serious predication error. The field-based experiments rely too much on the experiment data, which would not provide practical basis for policy makers. In order to avoid this situation, scholars such as Guo (Guo et al., 2013) proposed a carbon emission potential index model to estimate the emission reduction potential based on the status quo.

Summarily, existing studies have done much work on carbon emissions and provide us with the reference on carbon emission estimation, decomposition and reduction potential calculation. However, limitations still exist: (1) Despite that existing carbon emission reduction researches mainly focused on the field of fossil fuels or a specific activity (power sector or agricultural sector), few of them are conducted from the perspective of land use, especially the urban construction land. (2) Most studies related to urban construction are conducted at the national and provincial level by applying cross-sectional data. Few of them conducted time series investigation on estimation, decomposition and reduction potential calculation from urban construction land at the provincial level. Significant disparities are the most obvious characteristics among China's provinces and cities (Huo et al., 2020b), but there is a lack of long-term systematic analysis on the evolution trend of the spatial distribution pattern and reduction potential estimation of carbon emission of urban construction land in China from the view of land use (Shen, 2005). (3) In the process of decomposition and reduction potential estimation analysis, previous scholars are mainly taking the total carbon emission as the research object, which is unfair for local governments; different provinces and cities in China have differential original natural resources endowment and face different developing stages. The allocation target of carbon emission allowances based on per capita carbon emission intensity focuses on the equal distribution

of carbon emission rights, which has received special support from developing countries and has become an important standard for human well-being.

Therefore, this study aims at solving the above limitations and makes contribution to the current knowledge gaps in the following 3 aspects: (1) This study established a relative comprehensive research framework by taking the estimation of carbon emission decomposition and reduction potential analysis into consideration, which is an innovation work in research frame. (2) The research objective of this study is carbon emission from urban construction of 30 provinces in China over the period 2000–2018, filling the gap in the previous research at this scale. (3) The per capacity carbon emission is selected as the decomposition and reduction potential estimation calculation, which is distinguished from the existing that focus on the total carbon emission. Per capita carbon emissions' intensity is crucial as a key carbon control indicator, which can better cope with the fairness of the low-carbon transition at the micro-level and help promote regional carbon emissions reductions. Therefore, by applying the IPCC list, LMDI model and emission reduction index, this study can help the local government understand the tempo-spatial distribution patterns of carbon emission, identify the main driving factors behind the emission and design more feasible and differential carbon emission reduction strategies.

The remaining sections are listed as follows: The method and materials are presented in Sect. 2. Section 3 estimates and compares the urban construction land per capita carbon emission and intensity between 30 provinces in China from 2000 to 2018. The fourth section decomposes the driving factors of per capita carbon emissions from construction land. The carbon emission reduction potential of urban construction land in 30 provinces in China is explored in the fifth section. Section 6 presents the discussion, summaries of the conclusions and provides the policy implications.

## 2 Method and materials

### 2.1 Method

#### 2.1.1 IPCC framework

Reducing the carbon intensity of construction land is an important way to achieve China's carbon intensity reduction targets, and accurate emission estimation is the first stage. Refer to the IPCC accounting framework for energy consumption, industrial production and human resources carried by urban construction land. The carbon emissions of the absorbed land are calculated, and the calculation formula for the total carbon emissions carried by the construction land can be expressed as follows:

$$CE = CE_{\text{energy}} + CE_{\text{industry}} + CE_{\text{respiration}} \tag{1}$$

By calculating the product of the standard coal consumption of various energy sources and the corresponding carbon emission coefficient, the carbon emission of regional energy activities is obtained:

$$CE_{\text{energy}} = \sum_{i=1}^8 E_i * CEF_i \tag{2}$$

where  $i$  is the type of energy, which includes raw coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil and natural gas;  $E_i$  is the conversion coefficient between energy  $i$  and standard coal;  $CEF_i$  is the carbon emission coefficient of the energy source.

The calculation formula for carbon emissions in industrial production is:

$$CE_{\text{industry}} = \sum_{j=1}^3 P_j * IEF_j \quad (3)$$

where  $j$  is an industrial product category, which includes steel, cement and synthetic ammonia;  $P_j$  represents the production volume of industrial product  $j$ .  $IEF_j$  is the carbon emission of industrial product  $j$ .

The calculation formula of human respiratory carbon emissions is listed as follows:

$$CE_{\text{respiration}} = \text{POP} * \text{REF} \quad (4)$$

where POP is the number of permanent urban residents of each province. REF represents the annual per capita breathing carbon emissions.

Therefore, the per capita carbon emission is listed as follows:

$$A = \frac{C}{P} \quad (5)$$

where  $P$  is the permanent population of the city.  $C$  represents the national carbon emissions of urban construction land. Moreover, "carbon emission per capita" is replaced as "carbon emission" in the following texts.

The per capita carbon emission intensity of construction land refers to per capita carbon emission per unit construction land area, as shown in Eq. (6). This indicator spatially reflects the carbon emission burden generated by human activities. The larger the value indicates the carbon emission generated by this type of land use human activities, the more carbon emissions generated by human activities, the higher the economic benefits and the increased environmental burden.

$$\text{CI} = \frac{\text{CE}}{A} \quad (6)$$

where CI is the per capita carbon emission intensity of construction land (unit: t/km<sup>2</sup>); CE refers to the per capita carbon emission carried by construction land (unit: t); A represents the construction land area.

### 2.1.2 LMDI model for critical drivers of per capita carbon emissions

Kaya (1989) introduced an extensively applicable model to the analysis of carbon emissions during a seminar organized by IPCC. According to the previously established methodology, LMDI method is a relatively reasonable method among various methods of decomposing carbon emission drivers (Shao et al., 2018), and it usually established an equation which relates the economic, demographic, energy intensity, and energy emissions factors to estimate carbon emissions of human activities as Eq. (7):

$$\text{CO}_2 = \frac{\text{CO}_2}{\text{PE}} \times \frac{\text{PE}}{\text{GDP}} \times \frac{\text{GDP}}{\text{POP}} \times \text{POP} \quad (7)$$

where  $CO_2$ , PE and GDP denote the urban construction carbon emissions, urban energy consumption and gross domestic product. POP is the total domestic population, respectively. Based on the previously established methodology, factors in Kaya identity were decomposed following LMDI decomposition (Ang & Choi, 1997). Mathematically, the impact of different driving forces on per capita carbon emission of Eq. (7) can be expressed in the new form as Eq. (8):

$$PCC = \frac{CO_2}{POP} = \frac{CO_2}{PE} \times \frac{PE}{GDP} \times \frac{GDP}{POP} = EF \times PI \times GR \tag{8}$$

PCC is the ratio of urban construction land to population, namely per capita carbon emissions; it can be decomposed into 3 driving factors by applying the LMDI model: urban construction energy structure effect (EF), the energy efficiency effect (PI) and the economic effect (GR). EF denotes the ratio of amount of  $CO_2$  emitted per unit to the energy consumption (Huo et al., 2020b; Shao et al., 2018). PI is the ratio of energy consumption of urban construction land to the GDP, and GR denotes the proportion of GDP to the population, namely the economic effect.

The impact of different driving forces on per capita carbon emission was analyzed by Eq. (9) from the start year " $t=0$ " to the end year " $t=18$ "; changes in the impact at a given time " $\Delta C$ " are equal to Eq. (8), given as:

$$\Delta A = A_t - A_0 = \Delta A_F + \Delta A_I + \Delta A_R \tag{9}$$

where  $\Delta A_F$  is the energy structure effect,  $\Delta A_I$  represents the energy efficiency effect,  $\Delta A_R$  is the economic effect, and  $\Delta A_P$  represents the population effect. The results after decomposition are as Eqs. 10, 11, 12, 13:

$$\Delta A_F = \frac{A_{t-A_0}}{\ln(A_t/A_0)} \cdot \ln \frac{F_t}{F_0} \tag{10}$$

$$\Delta A_I = \frac{A_{t-A_0}}{\ln(A_t/A_0)} \cdot \ln \frac{I_t}{I_0} \tag{11}$$

$$\Delta A_R = \frac{A_{t-A_0}}{\ln(A_t/A_0)} \cdot \ln \frac{R_t}{R_0} \tag{12}$$

$$\Delta A_P = \frac{A_{t-A_0}}{\ln(A_t/A_0)} \cdot \ln \frac{P_t}{P_0} \tag{13}$$

### 2.1.3 Carbon emission reduction potential index

Due to the uneven level of urbanization in various regions in China, the challenges of carbon reduction in different provinces show significant disparity (Huo et al., 2020b). Therefore, inter-provincial heterogeneity should be considered when decomposing changes in the carbon emission of construction land. Particularly, as the ratio of per

capita carbon emission to the area of construction land, per capita carbon emission intensity is often used as an indicator of emission reduction potential assessment due to its consideration on heterogeneity of different regions referring to Guo et al. (Guo et al., 2013).

First, the study constructs the rate( $r$ ) of change in per capita carbon emission intensity. It can be expressed as the ratio of the per capita carbon emission intensity of China at the base year ( $A(CI)_0$ ) to per capita carbon emission change in the year  $t$  ( $\Delta A(CI)_t$ ):

$$r = \Delta A(CI)_t / \Delta A(CI)_0 \quad (14)$$

When the per capita carbon emission intensity of each province changes according to the national average rate of change, a reference per capita carbon intensity changes is shown as Eq. 13:

$$\Delta(CIR)_{kt} = r * (CI)_{k0} \quad (15)$$

where  $(CI)_{k0}$  is the per capita carbon emission intensity of province  $k$  in the base year. Therefore, the emission potential index  $ck$  of each province is defined as the ratio of the actual per capita carbon emission intensity change  $\Delta(CI)_{kt}$  to the reference per capita carbon emission intensity change  $\Delta(CIR)_{kt}$ :

$$ck = \Delta(CI)_{kt} / \Delta(CIR)_{kt} \quad (16)$$

When  $ck > 1$ , the actual per capita carbon emission intensity change is larger than average per capita carbon emission intensity, which means that the efficiency of province  $k$  in reducing per capita carbon intensity is higher than that of the national average level. When  $ck = 1$ , it means that the efficiency reaches the national average level. When  $ck < 1$ , it means that its efficiency is lower than the average level (Guo et al., 2013) (Table 1).

## 2.2 Data source

The data used in this paper, in the calculation of carbon emissions, and the total energy consumption of the 30 provinces from 2001 to 2018 are from the *China Energy Statistics Yearbook* (2001–2019). The data of production of industrial products during 2000–2018 are obtained from the *China Industrial Economic Statistic Yearbook* (2001–2019), the population data come from the *China Population Employment Statistics Yearbook* (2001–2019), and the construction land area data come from the “*China Urban Construction Statistical Yearbook* (2001–2019). The carbon emission factors and the various energy conversion standard coal coefficients are obtained from the Intergovernmental Panel on Climate Change (IPCC, 2006). Specially, the GDP during 2000 to

**Table 1** Description of carbon emission reduction potential evaluation indicators

$K$	Emission reduction potential evaluation
$K > 1$	Higher than the national average
$K = 1$	Reach the national average
$K < 1$	Lower than the national average

2018 is from the *China Statistical Yearbook (2001–2019)* and normalized to the 2000 constant price by using the consumer price index.

### 3 Estimation carbon emissions and carbon emissions intensity of construction land from 2000 to 2018

#### 3.1 Spatial-temporary analysis of carbon emissions from 2000 to 2018

As the main carbon source, urban construction land is of great significance to the realization of low-carbon land use (Shao et al., 2018). Under the pressure of reducing emissions, carbon emission right is one of the essential parts of human development right (Ding, 2010). More carbon emissions mean greater rights to development, and the allocation target of carbon emission allowances based on per capita carbon emissions focuses on the equal distribution of carbon emission rights, which has received special support from developing countries and has become an important standard for human well-being (Tian & Lin, 2021). Moreover, compared with the total carbon emission, per capita carbon emission is crucial as a key carbon control indicator, because it can cope with local efficiency and the fairness of the low-carbon transition at the micro-level, which will help promote regional and national carbon emissions reductions (Ding, 2010).

##### 3.1.1 Temporary analysis of carbon emissions from 2000 to 2018

Combing the data source and Eq. (1–5), the per capita carbon emissions of urban construction land in the 30 provinces of China during 2000 to 2018 were calculated. Figure 1 summarizes the temporal changing trend of China's per capita carbon emissions from 2000 to 2018.

According to Fig. 1, the carbon emission per capita has been growing almost straight from 2000 to 2011 and remained stable from 2011 to 2017. However, the per capita carbon emissions increase rapidly in 2017–2018 (as shown in Fig. 1). The above results show that the per capita carbon emissions in the country have shown an upward trend from 2000 to 2011. Due to the acceleration of urbanization and industrialization, social and economic construction and humanities construction have been greatly promoted, so energy

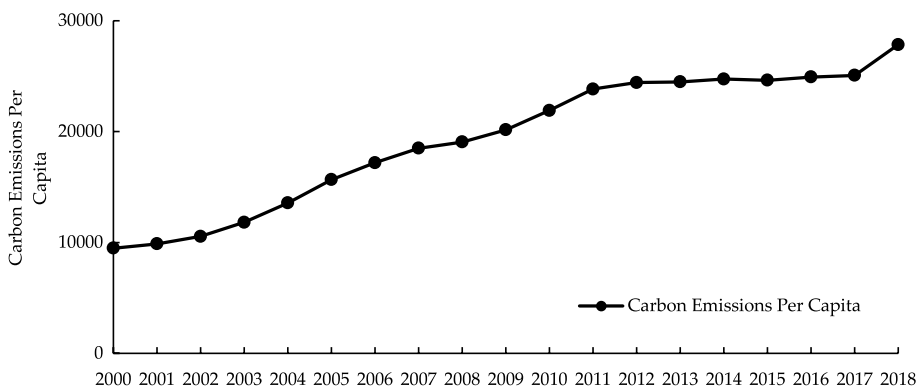


Fig. 1 Carbon emissions per capita of china from 2000 to 2018 (unit: t)

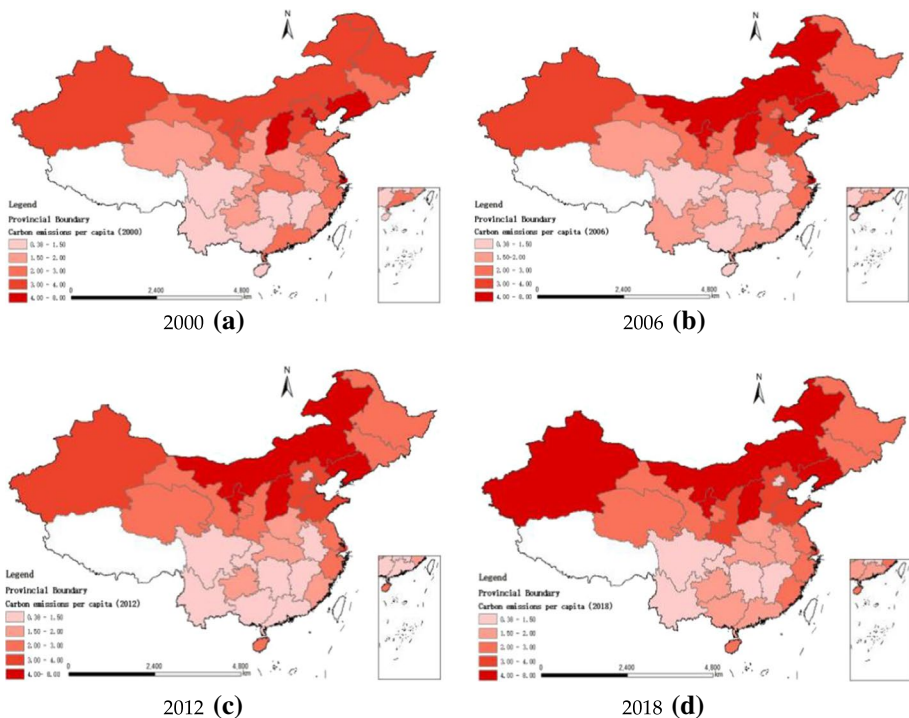


consumption, industrial production and population have increased significantly. The per capita carbon emission has also increased rapidly. From 2011 to 2017, the per capita carbon emissions remained stable. With the introduction of a carbon emission reduction plan, China promised in the Paris Agreement that it will reach its peak carbon emissions around 2030. With the introduction of a carbon emission reduction plan, China promised in the Paris Agreement that it will reach its peak carbon emissions around 2030. Therefore, carbon emissions have been included as a binding indicator into the national economic and social development mid-term and long-term plan, and initial results have been achieved. With the implementation of national policies, the carbon emissions have gradually stabilized. In 2018, the per capita carbon emissions of China growth rate rebounded, because the development speed of low-carbon technology cannot keep up with the growth of energy demand.

### 3.1.2 Spatial analysis of carbon emissions from 2000 to 2018

The spatial difference of the country's economic development has intensified the regional differentiation of per capita carbon emissions. In order to explore the spatial distribution characteristics of the per capita carbon emissions in the 30 provinces during 2000–2018, ArcGIS 10.2 software was used to visualize the measurement results (see Fig. 2).

In 2000, it can be clearly seen from Fig. 2 that Shanxi, Liaoning and Beijing-Tianjin have the highest level of per carbon emission. Most provinces in southern China have low



**Fig. 2** Carbon emissions per capita of China from 2000 to 2018 (unit: t)

carbon emissions per capita. In 2006, the spatial pattern of per capita carbon emissions showed that Shanxi, Liaoning, Ningxia and Inner Mongolia have entered the ranks of highest carbon per capita. However, per capita carbon emissions of Beijing–Tianjin begin to fall. In 2012, the provinces with high carbon emissions per capita remain unchanged. However, with the exception of Beijing–Tianjin, all northern provinces in China have reached higher per capita carbon emissions. Hainan, Zhejiang and Jiangsu also have higher per capita carbon emissions. In the year of 2018, Xinjiang has entered the ranks of the highest per capita carbon emissions. The per capita carbon emissions are also increasing in most provinces and cities southern China. China's per capita carbon emissions show the characteristics of agglomeration and contiguous distribution. In order to better promote urban development and construction, the energy demand continues to grow, but the development speed of high-efficiency renewable energy cannot keep up with the demand, leading to high carbon emissions. At the same time, the economic and geographic differences in various regions have further widened, leading to differences in per capita carbon emissions, which also reflects the relationship between the spatial pattern of the country's per capita carbon emissions and the regional economic development pattern.

### 3.2 Spatial-temporal analysis of carbon emission intensity from 2000 to 2018

Although the per capita carbon emissions of urban construction land can reflect the effect of emission reduction, it cannot clearly illustrate the emission reduction potential. Since carbon emission intensity represents the increase in carbon emissions per unit of output, it is often used as a fairer indicator for emission reduction potential evaluation (Ding, 2010). To measure the emission reduction potential of urban construction land in the 30 provinces, this paper analyzes the per capita carbon emission intensity of urban construction land in China from 2000 to 2018 by referring to the results of Sect. 3.1 and Eq. (6).

#### 3.2.1 Temporal analysis of carbon emission intensity from 2000 to 2018

Carbon emission intensity is not only affected by the total emissions, but also by the area of urban construction land. The per capita carbon emissions intensity from 2000 to 2018 of China is shown in Fig. 3.

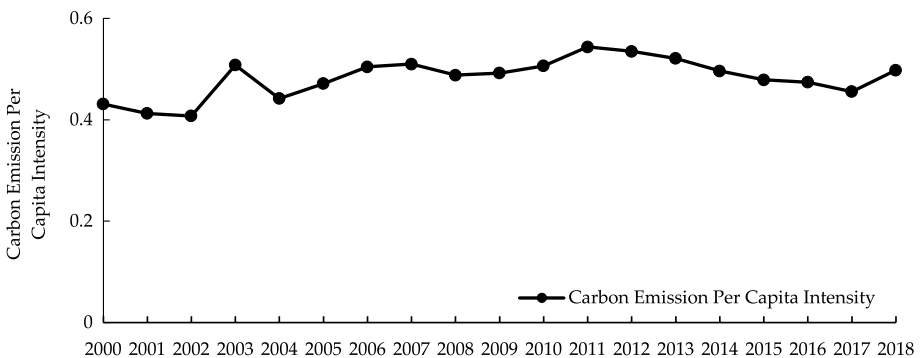


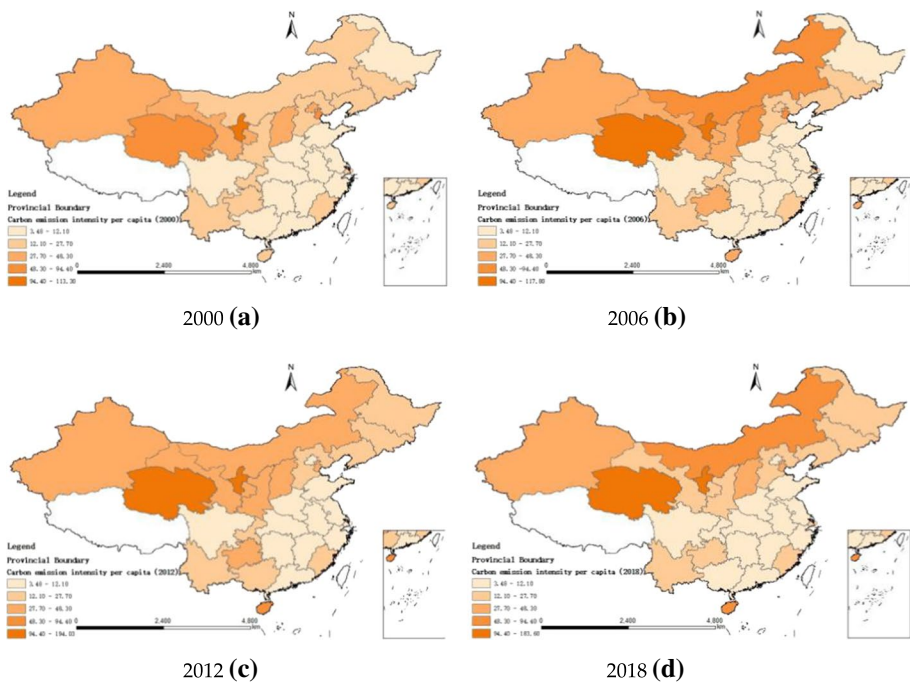
Fig. 3 Per capita carbon emissions intensity of China from 2000 to 2018 (unit: t/km<sup>2</sup>)

The per capita carbon emission intensity of urban construction land is related to the per capita carbon emission and the construction land area. From 2000 to 2002, the intensity of per capita carbon emissions decreased slowly. However, due to SARS occurrence in 2002, the economic in China, especially the industry, developed rapidly in 2003, and the per capita carbon emission intensity caused by the change in the industrial structure is more obvious. From 2004 to 2011, the intensity of per capita carbon emissions has shown a slow upward trend. In 2011, per capita carbon emission intensity reached its peak and then showed a decreasing trend. It was mainly affected by the carbon emission reduction policy brought by the Paris Agreement. In 2018, the economic development caused higher emission. The intensity of per capita carbon emissions has rapidly risen significantly. While developing the economy, the carbon emission intensity of my country's construction land has shown an upward trend in 2018, indicating that the carbon emissions caused by urban development in my country are still relatively high. In the process of urbanization, the expansion of construction land should be controlled, and land for carbon sinks such as grassland should be increased.

### 3.2.2 Spatial analyses of carbon emission intensity from 2000 to 2018

In order to explore the spatial distribution characteristics of China's per capita carbon emissions intensity, ArcGIS 10.2 software was used to visualize the measurement results (see Fig. 4).

According to Fig. 4, the per capita carbon emission intensity in Northern China is high from 2000 to 2018. Areas with higher per capita carbon emission intensity are relatively



**Fig. 4** The per capita carbon emissions intensity of China from 2000 to 2018 (unit:  $t/km^2$ )

stable, mainly in Qinghai and Ningxia. Although the highest intensity of carbon emissions per capita in provinces remained stable from 2000 to 2018, the spatial distribution of other carbon emission intensity areas has changed significantly. The areas with higher per capita carbon emissions first expanded and then contracted, while the low intensity areas shrink first and then expand, but the per capita carbon emission intensity of China's construction land still shows an upward trend. Specifically, (1) the highest intensity area of per capita construction land carbon emission began to expand, the low intensity area remained unchanged in space, and the other types of carbon emission intensity area showed an expansion trend from 2000 to 2006. (2) From 2006 to 2012, the highest intensity area of per capita construction land carbon emission remained unchanged, the higher intensity area expanded spatially, and the low-intensity area rapidly shrank. (3) From 2006 to 2012, the highest-intensity area of per capita construction land carbon emissions remained unchanged, the higher intensity area began to shrink in space, and the low intensity area gradually expanded.

#### 4 Decomposition of carbon emissions from urban construction land during 2000–2018

To explore the driving factors of the increasing per capita carbon emission trend, this study analyzed the carbon emissions through the mathematically modified LMDI model by referring to Eqs. (7, 8, 9, 10, 11, 12, 13). The driving factors were decomposed into the energy structure effect, the energy efficiency effect and the economic effect. The decomposition analysis of per capita carbon emission during 2000–2018 is illustrated in Fig. 5.

Energy structure denotes the ratio of amount of CO<sub>2</sub> emitted per unit to the energy consumption, and its contribution to per capita carbon emissions varies from each other when the energy consumption structure is different among provinces (Huo et al., 2020b). As shown in Fig. 5, the national energy structure effect for per capita carbon emissions fluctuated around 0 from 2000 to 2018, and its contribution to par capita carbon emissions stays stable because the energy consumption in China mainly relied on coal consumption (Wang et al., 2021). Therefore, optimizing the energy structure is conducive to achieving the “low-carbon” goal of energy emission reduction in urban area, so energy structure should be adjusted by reducing the proportion of coal consumption to the whole energy consumption.

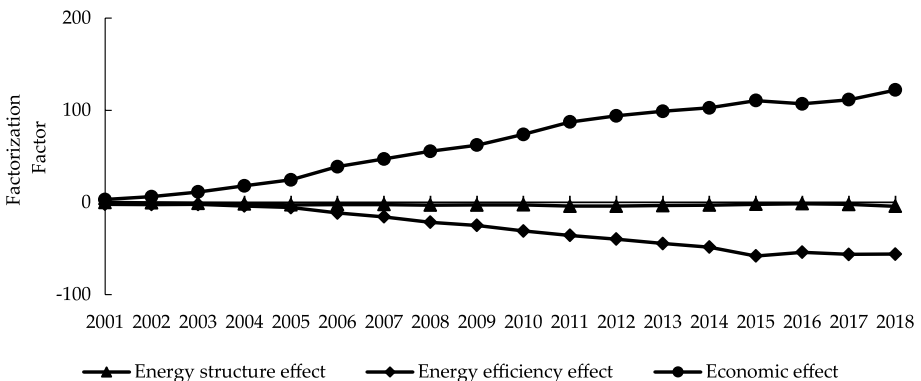


Fig. 5 The decomposition of the per capita carbon emissions

The energy efficiency effect has negative contribution to the per capita carbon emissions during the research period, which played a fundamental part in slowing down per capita carbon emission. Specifically, the energy efficiency effect showed an increasing inhabiting trend in slowing down the national per capita carbon emission, which is the result of industry updating and innovation of clean energy in China (Khan & Pinter, 2016). Based on the decomposition result of per capita carbon emissions, the economic effect has positively contribution to per capita carbon emission. In the early 2000s, the economic effect first showed a rapid increase trend from 2000 to 2018, and the increase in per capita carbon emissions was largely due to the stimulus effect of GDP. Besides, the contribution of economic effects from 2000 to 2018 is greater than the sum of the contribution of energy structure effects and energy efficiency effects to the per capita carbon emissions. It can be seen that the economic effect is a key factor in the growing trend of per capita carbon emissions.

To further investigate the regional characteristics of critical drivers of carbon emissions, we analyzed the driving factors of per capita carbon emissions in China's 30 provinces from 2000 to 2018 (Fig. 7). The energy structure effects vary from each other due to the different energy consumption structure in each province (Huo et al., 2020b). Specifically, the effects of energy structure and energy efficiency for per capita carbon emission are both negative in Fujian, Shandong, Henan, Hunan and Yunnan, and the energy structure effect has a greater impact on per capita carbon emissions than the energy efficiency effect. Despite that the economic effect has positive impact on per capita carbon emission, changes in the energy structure have effectively offset some of the carbon emissions brought about by urban economic development. This is due to the continuous optimization of the energy structure, the use of clean energy and renewable energy to replace the long-term use of primary energy and the burning of fossil fuels, while improving the utilization of clean energy, thereby reducing the use of high carbon emission energy such as coal and coke. Contrary to the national scale, the effects of energy structure and economic per capita carbon emission on province level are both positive in Hainan. The energy efficiency for per capita carbon emission is negatively affected. In Xinjiang and Ningxia, the energy structure effect and the energy efficiency effect for per capita carbon emissions are small with little change. And the economic effect for per capita carbon emission is positive affected. We can find that the industries in these areas are underdeveloped. At the same time, the energy structure of these regions has not been optimized, and the utilization rate of clean energy is low. Therefore, the impact of energy structure effect and energy efficiency effect on per capita carbon emissions is quite different with the result of the national scale.

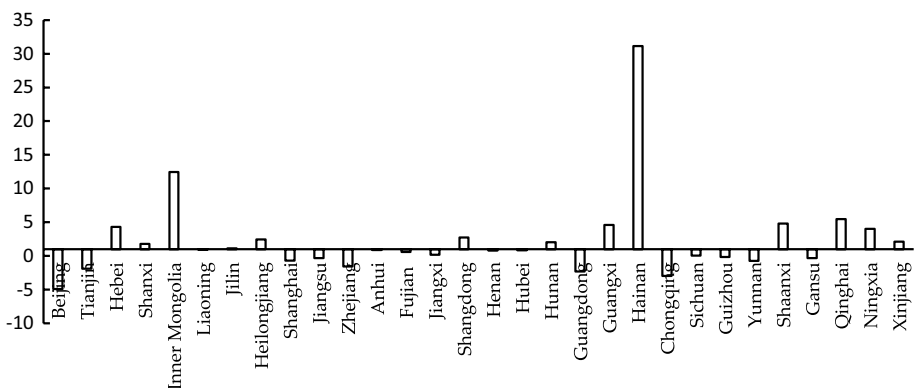
## 5 Assessment of carbon emission reduction potential during 2000–2018

Different regions are at different levels of economic development, and their emission reduction strategies also face significant disparities. Regions with higher level of economic development need to reduce emissions while maintaining the humanistic environment. Regions with a lower level of economic development peruse to achieve emissions reduction goals while seeking economic development. Calculating carbon emission reduction potential based on the national level is more meaningful to achieve carbon emission reduction commitments. Moreover, due to the uneven level of urbanization

in various regions in China, the challenges of carbon reduction in different provinces show significant disparity (Huo et al., 2020b). Assessment of carbon emission reduction potential at provincial level is especially meaningful for the local government to do practical implementation work. Therefore, inter-provincial heterogeneity should be considered when decomposing changes in the carbon emission of construction land. Particularly, as the ratio of per capita carbon emission to the area of construction land, per capita carbon emission intensity is often used as an indicator of emission reduction potential assessment due to its consideration on heterogeneity of different regions (Ding, 2010; Huo et al., 2020b).

In order to achieve a more realistic horizontal comparative analysis of the emission reduction potential between regions, the carbon emission potential index model is put forward to analyze the carbon emission reduction potential of urban construction land by referring to Guo et al. (Guo et al., 2013). Based on the data of 30 province-level regions in China from 2000 to 2018, this study calculated the carbon emission reduction potential indexes. This result can provide a basis for the government to formulate more precisely inter-provincial carbon rights allocation and emission reduction responsibility allocation. The result is shown in Fig. 6.

According to the results of the model, the potential indexes of Hebei, Shanxi, Inner Mongolia, Jilin, Heilongjiang, Shandong, Hunan, Guangxi, Hainan, Shaanxi, Qinghai, Ningxia, Xinjiang in 2000–2018 are greater than 1 and indicate the emission reduction potentials of these provinces are higher than the national average (Fig. 6). Most of the above provinces are located in the northern regions with high per capita carbon emissions. Although these provinces have high per capita carbon emissions, the government has put forward a lot of policies to reduce carbon emissions. Therefore, in the past few decades, they have made a greater contribution to carbon reduction. However, the carbon emission reduction potential indexes of rest provinces are less than 1, which showed that the carbon emission reduction in these regions had not reached the national average level. These provinces are mainly concentrated in the southern China. In order to accelerate the realization of low-carbon growth and sustainable development goals, China needs to make further efforts to tap the carbon emission reduction potential of relevant provinces in order to greatly increase its carbon emission reduction contribution. All provinces should reasonably control the expansion of construction land, increase carbon sinks, and rationally lay out the land structure.



**Fig. 6** Emission reduction potential index of China from 2000 to 2018

## 6 Conclusions and discussion

### 6.1 Conclusions

To analyze the temporal and spatial distribution of China's construction land carbon emissions, determine its critical drivers, and explore the potential for emission reduction, this study used the IPCC, Kaya identity, LMDI decomposition and emission reduction potential model analysis from 2000 to 2018. The estimation, decomposition and assessment analysis presented in this study can also be generally accepted to other regions at different scale. The results revealed that: (1) for the perspective of temporal change, the per capita carbon emissions from 2000 to 2018 showed an upward trend. And, the per capita carbon emission intensity showed a slight growth trend. In terms of spatial distribution, China's per capita carbon emissions show the characteristics of agglomeration and contiguous distribution. The carbon emission intensity per capita in the Northern China is higher than in the southern part from 2000 to 2018. Centers with higher per capita carbon emission intensity are relatively stable, mainly in Qinghai and Ningxia. (2) Among the drivers considered in this study during the research period, energy structure and energy efficiency were the inhabiting factors of per capita carbon emissions. The effect of economic level exceeds 0 both in the national and provincial level; the growing trend of economy leads to the increase in per capita carbon emissions. Specially, these driving factors are spatially different. However, in the long term, the energy efficiency and energy structure are essential to mitigate future carbon emissions and achieve sustainable economic development. (3) From 2000 to 2018, only 13 provinces in China had a carbon emission reduction potential index greater than 1, and most of them were located in areas with high carbon emissions in China. They are the key area for emission reduction.

### 6.2 Discussion

This study measures the per capita carbon emissions of construction land in 30 provinces across the country, systematically analyzes the changes in temporal and spatial patterns, identifies differences between regions, and establishes emission reduction models to provide theoretic support for policy makers. However, several limitations still exist: (1) The study was conducted from the perspective of construction land carbon emission. However, the rural construction land and green spaces in urban areas were not included in the research area because the carbon emissions from them are tiny when compared with the urban construction land, which may make the estimation results inaccurate. (2) The carbon emission potential reduction model used in this study is a comparative indicator, it only makes sense when make comparisons in the research area, but unable to make comparisons between China and other countries. (3) All the data collection and analyses work are done at the national or provincial level, great differences may exist within one province, and more researches on a smaller scale are the future directions.

In light of the conclusions of this research, policy recommendations can be made from the following aspects to achieve effective carbon emission reduction in urban construction land. Those implications are also useful for regions with similar conditions. Firstly, the total amount of carbon emission from urban area should be controlled. Specifically, all provinces should control the expansion of construction land in a reasonable and orderly manner, accelerate the conversion of unused and other land use types into forest land,



garden land, and pasture land (e.g., *Returning Cropland to Forestland Program*), which could increase the amount of carbon sinks effectively and achieve China's carbon neutral target fundamentally. Secondly, more investments should be put on the innovation of the clean energy such as hydro-electric power and wind power. Although the government has promised to increase the share of non-fossil fuels in primary energy consumption to about 25% by 2030 (Tian & Lin, 2021), China is still relatively lagging in the development of new clean energy technologies when comparing with developed countries (Liu et al., 2015). Secondly, in terms of economic effect, the government should take active actions to design a more sustainable developing mode in the urban area. This mode can reduce the proportion of energy-intensive industries and promote the cultivation low-carbon industries. For example, when establishing development area in cities, only low-carbon companies can be allowed to be set up. According to the actual situation of each province, improve the existing technology to minimize carbon emissions while vigorously developing new technologies and carrying out extensive promotion. Thirdly, differentiated emission reduction policies should be formulated by local governments according to the carbon significant disparities of each province.

### Appendix. 1

See Fig. 7

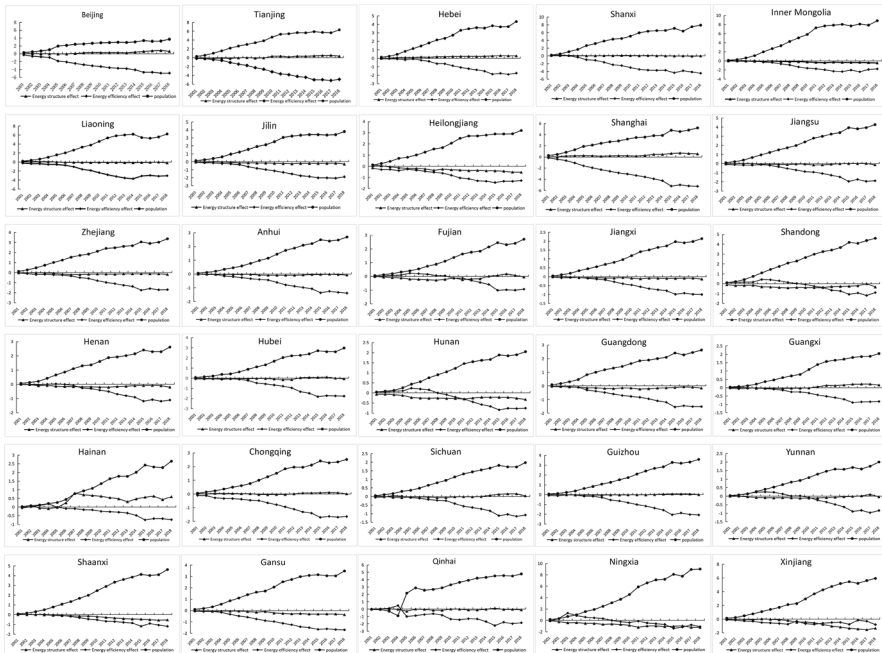


Fig. 7 The decomposition of carbon emissions per capita in China's provinces from 2000 to 2018



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## References

- Ang, B. W., & Choi, K. H. (1997). Decomposition of aggregate energy and gas emission intensities for industry: A refined Divisia index method. *The Energy Journal*, *18*(3), 59–73.
- Ang, B. W., & Liu, N. (2007). Energy decomposition analysis: IEA model versus other methods. *Energy Policy*, *35*(3), 1426–1432.
- Cai, B. F., Cao, L. B., Lei, Y., et al. (2021). China's carbon emission pathway under the carbon neutrality target. *China Population, Resources and Environment*, *31*(1), 1–7. in Chinese.
- Chuai, X., Huang, X., Wang, W., et al. (2015). Land use, total carbon emissions change and low carbon land management in coastal Jiangsu China. *Journal of Cleaner Production*, *103*(15), 77–86.
- Churkina, G. (2008). Modeling the carbon cycle of urban systems. *Ecological Modeling*, *216*(2), 107–113.
- Book Cubasch, U., Hu Z. Z. (2001) Projections of future climate change, in IPCC 2001. Projections of Future Climate Change.
- Online document Ding, Z. L. (2010, Feb 10). Accumulated per capita carbon emission is the best indicator to realize the principle of justice and fairness. OER Commons. Retrieved March 5, 2021 from Chinanews.
- Eggleston, H. S., Buendia, L., Miwa, K., et al. (2006). *2006 IPCC guidelines for national greenhouse gas inventories*. IGES Press.
- Fan, F., & Lei, Y. (2017). Factor analysis of energy-related carbon emissions: A case study of Beijing. *Journal of Cleaner Production*, *163*, 277–283.
- Ghaffar, A., & Vilas, N. (2012). Exercising multidisciplinary approach to assess interrelationship between energy use, carbon emission and land use change in a metropolitan city of Pakistan. *Renewable and Sustainable Energy Reviews*, *16*, 775–786.
- Grimm, N. B., Faeth, S. H., Golubiewski, N. E., et al. (2008). Global change and the ecology of cities. *Science*, *319*, 756–760.
- Guo, J., Liu, C. X., & Sun, P. (2013). Carbon Emissions from industrial sectors in China: Driving factors and the potential for emission reduction. *Journal of Resources and Ecology*, *4*, 132–140.
- Houghton, R. A., & Hackler, J. L. (2001). Emissions of carbon from forestry and land-use change in tropical Asia. *Global Change Biology*, *12*, 1365–2486.
- Houghton, R. A., Hobbie, J. E., Melillo, J. M., et al. (1983). Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO<sub>2</sub> to the atmosphere. *Ecological Monographs*, *53*(3), 235–262.
- Huo, T., Li, X., Cai, W. G., Zuo, J., & Wei, H. (2020). Exploring the impact of urbanization on urban building carbon emissions in china: Evidence from a provincial panel data model. *Sustainable Cities and Society*, *56*, 102068.
- Huo, T. F., Ma, Y. L., Yu, T., et al. (2020). Decoupling and decomposition analysis of residential building carbon emissions from residential income: Evidence from the provincial level in China. *Environmental Impact Assessment Review*, *86*, 1–12.
- Jones, C., & Kammen, D. M. (2014). Spatial distribution of U.S. household carbon footprints reveals suburbanization undermines greenhouse gas benefits of urban population density. *Environmental Science & Technology*, *48*(2), 895–902.
- Jing, Q., Bai, H., Luo, W., Cai, B., et al. (2018). A top-bottom method for city-scale energy-related CO<sub>2</sub> emissions estimation: A case study of 41 Chinese cities. *Journal of Cleaner Production*, *202*, 444–455.
- Book Kaya, Y. (1989). Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios. Intergovernmental panel on climate change (IPCC). Response strategies working group: Geneva, Switzerland.
- Khan, F., & Pinter, L. (2016). Scaling indicator and planning plane: An indicator and a visual tool for exploring the relationship between urban form, energy efficiency and carbon emissions. *Ecological Indicators*, *67*, 183–192.
- Liu, Z., Guan, D., Wei, W., et al. (2015). Reduced carbon emission estimates from fossil fuel combustion and cement production in China. *Nature*, *524*(7565), 335–338.
- Lai, L., Huang, X., Yang, H., et al. (2016). Carbon emissions from land-use change and management in China between 1990 and 2010. *Science Advances*, *11*, 1601063.

- LuXia, H., Ji, H., Kun, Y., et al. (2016). Analysis of the built-up area's carbon emission intensity and its regional disparity in China. *Environmental Science and Technology*, 39(8), 185–192.
- Li, H. (2017). Talking about China's carbon emission reduction problem after Paris climate conference. *Modern Business*, 11, 163–164.
- Li, J. X., Chen, Y. N., Li, Z., et al. (2018). Quantitative analysis of the impact factors of conventional energy carbon emissions in Kazakhstan based on LMDI decomposition and STIRPAT model. *Journal of Geographical Sciences*, 28(7), 1001–1019.
- Li, Z., Chen, Y., Zhang, Q., & Li, Y. (2020). Spatial patterns of vegetation carbon sinks and sources under water constraint in central Asia. *Journal of Hydrology*, 590, 125355.
- Li, D. Z., Huang, G. Y., Zhu, S. Y., et al. (2021). How to peak carbon emissions of provincial construction industry? Scenario analysis of Jiangsu province. *Renewable and Sustainable Energy Reviews*, 144, 110953.
- Oh, B. K., Choi, S. W., & Park, H. S. (2016). Influence of variations in CO<sub>2</sub> emission data upon environmental impact of building construction. *Journal of Cleaner Production*, 140(3), 1194–1203.
- Qing, Y. Y. (2010). Land use change and carbon cycle. *China Land Science*, 24, 7–12.
- Qian, H., Cai, M., & Wu, K. (2018). Analysis of carbon emissions effect of construction land in Shanghai. *Journal of Hefei University of Technology (Natural Science)*, 41, 1414–1419.
- StuiverM. . (1978). Atmospheric carbon dioxide and carbon reservoir changes. *Science*, 199(4326), 253–258.
- Shen, Q. (2005). Study on urban energy sustainable development: A view from urban planning. *Urban Planning Forum*, 6, 41–47.
- Shan, Y., Guan, D., Liu, J., Mi, Z., et al. (2017). Methodology and applications of city level CO<sub>2</sub> emission accounts in China. *Journal of Cleaner Production*, 161, 1215–1225.
- Shao, W., Liu, J., Yang, Z., et al. (2018). Carbon reduction effects of sponge city construction: A case study of the city of Xiamen. *Energy Procedia*, 152, 1145–1151.
- Shen, L., Wu, Y., Lou, Y., et al. (2018). What drives the carbon emission in the Chinese cities? -A case of pilot low carbon city of Beijing. *Journal of Cleaner Production*, 174, 343–354.
- Shi, X. R., Zheng, Y. X., Lei, Y., et al. (2021). Air quality benefits of achieving carbon neutrality in China. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2021.148784>
- Tallarico, C. D., & Johnson, A. C. (2010). The implications of global ecological elasticity for carbon control: A STIRPAT formulation. *Journal of Management Policy and Practice*, 11, 86–94.
- Tan, S., Yang, J., Yan, J., et al. (2016). A holistic low carbon cityindicator framework for sustainable development. *Applied Energy*, 185, 1919–1930.
- Tian, Y., & Lin, Z. J. (2021). Provincial distribution of China's carbon emission rights and assessment of its emission reduction potential under the Paris agreement. *Journal of Natural Resources*, 36, 921–933.
- Wang, W., & Zheng, G. (2012). *Annual report on actions to address climate change: climate finance and low carbon development*. Social Sciences Academic Press. in Chinese.
- Wang, G., Han, Q., & Vries, B. D. (2020). A geographic carbon emission estimating framework on the city scale. *Journal of Cleaner Production*, 244(1), 118793.
- Wang, B., He, L., Yuan, X. C., et al. (2021). Carbon emissions of coal supply chain: an innovative perspective from physical to economic. *Journal of Cleaner Production*, 2, 126377.
- Yao, G., Wen, Y., Qiang, C., et al. (2020). No tillage and previous residual plastic mulching with reduced water and nitrogen supply reduces soil carbon emission and enhances productivity of following wheat in arid irrigation areas: Sciencedirect. *Field Crops Research*, 262, 108028.
- Zhao, R. Q., Huang, X. J., Yang, Z. T., et al. (2013). Carbon effect evaluation and low-carbon optimization of regional land use. *Transactions of the Chinese Society of Agricultural Engineering*, 29, 220–229.
- Online document Zhang, L., Qin, Y., Zhang, J., et al. (2013). Spatial differentiation of urban carbon emissions: An exploratory spatial data analysis in Beijing. OER Commons. Retrieved March 7, 2020 from The 21st International Conference on Geoinformatics.
- Zhu, E., Deng, J., Meng, M., et al. (2018). Carbon emissions induced by land-use and land-cover change from 1970 to 2010 in Zhejiang China. *Science of the Total Environment*, 646(1), 930–939.
- Zhang, W., & Zhou, T. (2020). Increasing impacts from extreme precipitation on population over China with global warming. *Science Bulletin*, 65(3), 243–252.
- Zhang, J., Fan, Z., Chen, Y., et al. (2020). Decomposition and decoupling analysis of carbon dioxide emissions from economic growth in the context of China and the ASEAN countries. *Science of the Total Environment*, 714(4), 136649.