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Abstract: In order to obtain detailed city-level carbon emission data, this paper constructed a model to estimate the urban CO_2 emissions in 2000, 2005 and 2013, using the combined data of DMSP/OLS nighttime light data and the provincial energy statistical yearbook data. It is found that there is a clearly linear correlation between the city nighttime light and the urban CO_2 emissions. We then calculated and analyzed the growth of urban built-up areas and carbon emissions in the different time periods at both the national level and the four economic zones in China. It is shown that a good fitting relationship between them with the R^2 at 0.6188 in 2000, 0.7132 in 2005 and 0.7195 in 2013. The growth rate of developed land area is 13.4% from 2000 to 2005 and 15.9% from 2005 to 2013. During the same period, the CO_2 emissions were also increasing, at an average annual growth rate of 12.2% from 2000 to 2005 and 6.5% from 2005 to 2013. From the spatial point of view, carbon emissions are far greater in the eastern region of China than in western China. The city carbon emissions are the highest in major metropolitan cities such as Beijing, Shanghai and Guangzhou. The per capita carbon emissions are also higher in the east, which is consistent with the people's higher living standards. In some cities with large energy and heavy industry concentrations, especially in the northeastern and western regions, the growth rate of carbon emissions has risen faster than other cities.

Key words: DMSP/OLS nighttime light data; Carbon emissions; Temporal and spatial analysis.

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Abstract: In order to obtain detailed city-level carbon emission data, this paper constructed a model to estimate the urban CO_2 emissions in 2000, 2005 and 2013, using the combined data of DMSP/OLS nighttime light data and the provincial energy statistical yearbook data. It is found that there is a clearly linear correlation between the city nighttime light and the urban CO_2 emissions. We then calculated and analyzed the growth of urban built-up areas and carbon emissions in the different time periods at both the national level and the four economic zones in China. It is shown that a good fitting relationship between them with the R^2 at 0.6188 in 2000, 0.7132 in 2005 and 0.7195 in 2013. The growth rate of developed land area is 13.4% from 2000 to 2005 and 15.9% from 2005 to 2013. During the same period, the CO_2 emissions were also increasing, at an average annual growth rate of 12.2% from 2000 to 2005 and 6.5% from 2005 to 2013. From the spatial point of view, carbon emissions are far greater in the eastern region of China than in western China. The city carbon emissions are the highest in major metropolitan cities such as Beijing, Shanghai and Guangzhou. The per capita carbon emissions are also higher in the east, which is consistent with the people's higher living standards. In some cities with large energy and heavy industry concentrations, especially in the northeastern and western regions, the growth rate of carbon emissions has risen faster than other cities.

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1.Introduction

Global climate change has become a critical global issue with severe threats over environment, economic development, and public health (Zhou et al.,2013). As the main driving force of climate change since the mid-20th century, the carbon dioxide (CO_2) greenhouse gas (GHG) generated by human activities has attracted much attention due to its huge volume. Carbon emissions from energy consumption caused by the burning of fossil fuels, mainly coal, oil and natural gas, are the main sources of GHG emissions generated by human activities. Many scholars have conducted in-depth research on carbon energy emission calculations, emission reduction strategies and influencing factors (Zhang Y.et al.,2011;Dong J. and Zhang X.,2010.Chenet al., 2007;Wang T. and Watson, 2010). During the past decades, China has experienced rapid economic growth. It is of great implications to investigate the environmental effect of the dramatic changes of land use and energy consumption for policy making towards sustainable development. Therefore, it is necessary to develop reliable approaches to estimate and analyze carbon emissions in different economic regions and implement strategic plans for carbon emission reduction.

The administrative regimes of China are divided into three levels: provincial level, municipal level and county level. The statistical data of energy carbon emissions in China are usually collected at the national or provincial level by the National Bureau of Statistics and its affiliated agencies. Since the detailed city-level data is comparatively rare, it is difficult to analyze the temporal trends and spatial patterns of the carbon emissions at micro scale. Therefore, more advanced technique is needed to assess carbon emissions in China. Due to the limited sources of energy data in China, the related research (Zhao et al.,2010; Wang and Zhu, 2008; Su, 2015) mainly used energy statistics to calculate the energy consumption of CO_2 emissions according to the IPCC standard. Up to now, the commonly used approaches for calculating carbon emissions in the world are the material balance algorithm, life cycle method, emission coefficient method, model method, and the method of decision tree of real objects (IPCC. 1990, 2001, 2006, 2007; Jarvis,et al., 1997.;Lee,1998;Yadvinder Malhi,et al.,1998;Wang and Gu, 2006;Che, 2010). Based on detailed fuel classification, Schimel et al. (Schimel D S, et al. 1995) estimated the amount of global anthropogenic CO_2. Their results show that the consumption of fossil fuels and cement production in the 1980s accounted for 78% of the world's total anthropogenic CO_2 emissions. Jae Hyun and Tae Hoon (JaeHyun Park and TaeHoon Hong,2013) adopted the fuel CO_2 estimation method provided by IPCC and estimated the seasonal emission of Korean energy CO_2 using the energy consumption data provided by Korea's energy statistics system and conducted correlation analysis with economic data and energy data. Iihan and Ali (Iihan O. and Ali A. ,2010) analyzed the long-term causality between Turkey's carbon emissions and economic growth, energy consumption, and employment, using CO_2 data provided by the World Development Institute with an auto-regressive co-integration method. The model method usually uses biogeochemical models to simulate the process of the ecological carbon cycle to obtain the flux of GHG, such as the MS-MRT model used in the Kyoto Protocol and the SDA model used in the United States for carbon emissions.

Based on the research background and knowledge gap, this paper constructed a model, aiming at estimating and calculating the municipal carbon emissions of China using the nighttime lighting data and provincial-level carbon emissions data.

2. Methods and data

2.1 Study area and data sources

The study area covers mainland China, excluding Hong Kong, Macao, and Taiwan. The spatial distribution of CO_2 emissions in mainland China was analyzed at the provincial and municipal levels.

Five main types of data sets were used in this study:

(1) The DMSP/OLS nighttime lighting data in 2000, 2005 and 2013.This data was obtained from the NGDC (National Geophysical Data Center), a unit of NOAA (National Oceanic and Atmospheric Administration) of the United States. The data with the spatial resolution of 30 arc seconds included stable light from cities and towns of human activities. The instantaneous light of transient events such as fire and abandoned combustion have been eliminated. Because there were a few differences and some noise, it was also necessary to adjust these night light data for de-noising, cutting, relative radiation calibration and geographic coordinate conversion before using them. The data was used to get light brightness values and extract urban and urban built-up areas.

(2) Landsat TM image data. The Landsat TM5 image data for Beijing in 2005 was collected to validate the extraction accuracy of urban built-up areas.

(3) Statistical yearbook data of provincial energy consumption in mainland China (excluding Hong Kong, Macao and Taiwan) in 2000, 2005, and 2013. The energy data reports the consumption of Raw Coal, Coke, Crude, Gasoline, Kerosene, Diesel, Fuel Oil, Natural Gas, Electricity, and other fossil fuels.

(4) Population data of cities in the year 2000, 2005, and 2013.

(5) Provincial and municipal administrative map of China.

2.2 Methods

Fig. 1 presents the overall research ideas and technical route of this paper. In this study, we use night lighting data to extract urban built-up areas in China, and verify the accuracy of extraction with TM data, in order to make a basis for counting the lighting brightness values in provinces and municipalities of China.

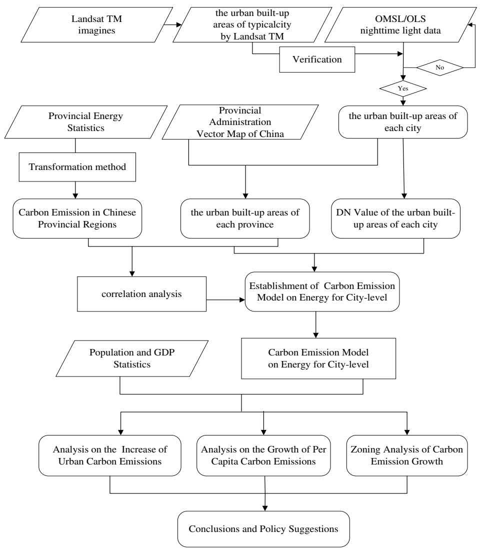


Fig.1 The Technology Roadmap

The detailed analyzing process is as followed:

Firstly, nighttime lighting data is processed, including image projection conversion, re-sampling, and cropping. The original images that are not radiometrically calibrated are mutually corrected, and the series images are subjected to steps of year fusion and inter-annual correction. Secondly, carbon emissions of each province are calculated using the statistical yearbook data. Thirdly, we construct an urban carbon emissions estimation model based on regression analysis of carbon emissions and lighting brightness of each province. Finally, the characteristics of urban carbon emissions, urban expansion and provincial carbon emissions in spatial-temporal perspective are analyzed.

2.2.1 Urban Area Extraction

Referring to Li et al. (2019), the urban area to be extracted can be divided into three parts, demarcation zone, urban area outside the demarcation zone, and urban area within the demarcation zone. After obtaining the urban area and the area within the demarcation zone, we can then calculate the whole urban area of each city. The whole urban area of each city is composed of two parts, one is the urban area within the demarcation zone, the other is the main urban area outside the demarcation zone. So, the whole urban area can be expressed as formula (1):

$$\text{whole urban area} = \text{main urban area} + \text{urban area(within the demarcation zone)} \quad (1)$$

2.2.2 Construction of the municipal energy carbon emission model

Similar to the related literature (Elvidge, et al., 1997; Doll et al., 2000, 2010; Raupach et al., 2010; Meng et al., 2014; Su et al., 2014), a city-level CO_2 emissions estimation model can be constructed if the nighttime light correlates to the total yearly carbon emissions of all provinces. The inversion model is shown in equation (2):

$$\text{City } CO_2 \text{ emissions} = \frac{\text{Provincial } CO_2 \text{ emissions}}{\text{Provincial nighttime light brightness}} \times \text{City nighttime light brightness} \quad (2)$$

2.2.2.1 Calculation of Energy Carbon Emissions

The provincial carbon emission data used in this paper is collected from the statistical yearbooks of various provinces in 2000, 2005, and 2013, reporting the carbon emission from the consumption of raw coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, natural gas, and electricity. The total yearly CO_2 values of all the provinces in 2000, 2005, and 2013 were calculated using the carbon emission factor formula (Su et al., 2015; Li et al., 2019; Che, 2010) shown in equation (3):

$$CO_2 = \frac{44}{12} \times \sum_{i=1}^{9} K_i E_i \quad (3)$$

Where E_i is the consumption of energy i, according to the standard coal unit, 10^4t; K_i is the coefficient of carbon emission of energy i, (10^4t carbon)/(10^4t standard coal); i is the type of energy, and the value of K_i is calculated according to the default value of the IPCC Carbon Emissions Calculation Guidelines.

The carbon emission factors for energy (IPCC, 2006,2013; Song, 2012; Zhou,2013) are shown in Table1:

Table1 Energy Emission Factor Table

Energy Type	Raw Coal	Coke	Crude	Gasoline
Converted to standard coal (t standard coal/t)	0.7143	0.9714	1.4286	1.4714
Carbon emission coefficient (10^4t carbon/10^4t standard coal)	0.7559	0.855	0.5857	0.5538

Energy type	Kerosene	Diesel	Fuel Oil	Natural Gas	Electricity
Converted to standard coal (t standard coal/t)	1.4714	1.4571	1.4286	1.33	0.345

Carbon emission coefficient (10^4t carbon/10^4t standard coal)	0.5714	0.5921	0.6185	0.4483	0.272

3. Results and Analysis

3.1 Extraction of urban area

Fig.2 shows the final construction maps in year 2000, 2005, and 2013. The urban area of China increased by 13.4% from 2000 to 2005, and 15.9% from 2005 to 2013.

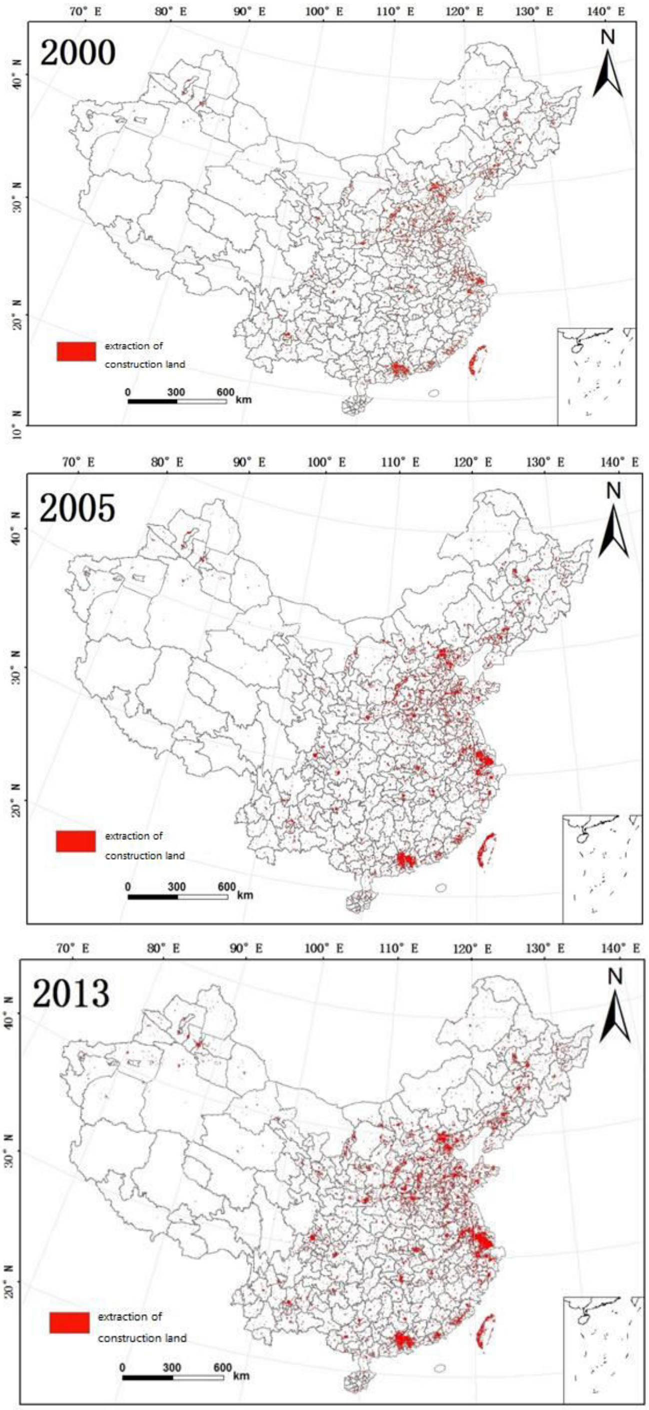
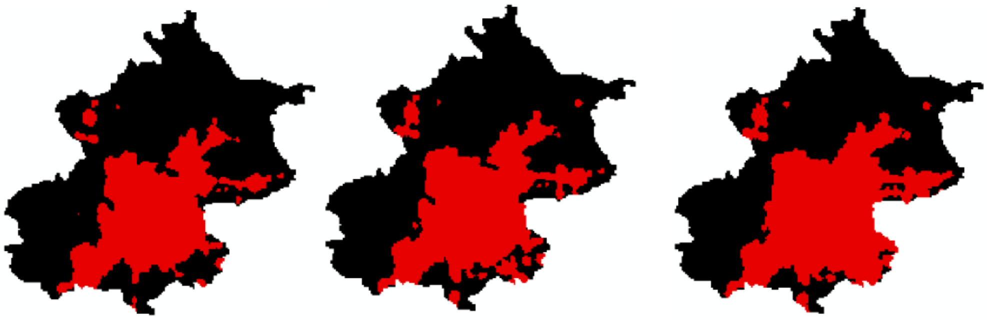


Fig. 2. Extracted China urban area



2000 2005 2013

Fig. 3. Change of urban area in Beijing

3.2 Accuracy Verification results

We further accurately calibrated the extracted urban area in this paper. Given the relatively high spatial resolution of Landsat TM images (30m×30m), scholars generally believe that the construction of map spots based on TM image data extraction is a reliable verification data source (Cao et al., 2009; He et al., 2006). Su et al., (2015) used TM image data to calibrate the extracted urban areas based on DMSP/OLS nighttime light data, and their results showed a significant correlation between the total number of pixels of the urban area extracted by the two datasets.

In this paper, the accuracy of the DMSP/OLS nighttime lighting data was calibrated by using the TM data image map of Beijing in 2005. The verification results presented in Fig.4 suggest a highly consistent relationship between the urban areas extracted respectively by light data and TM data. The difference between the number of pixels is 528, and the accuracy reaches 90.3%. Therefore, it is scientifically feasible to use the nighttime lighting data neighborhood analysis method to extract China's urban area.

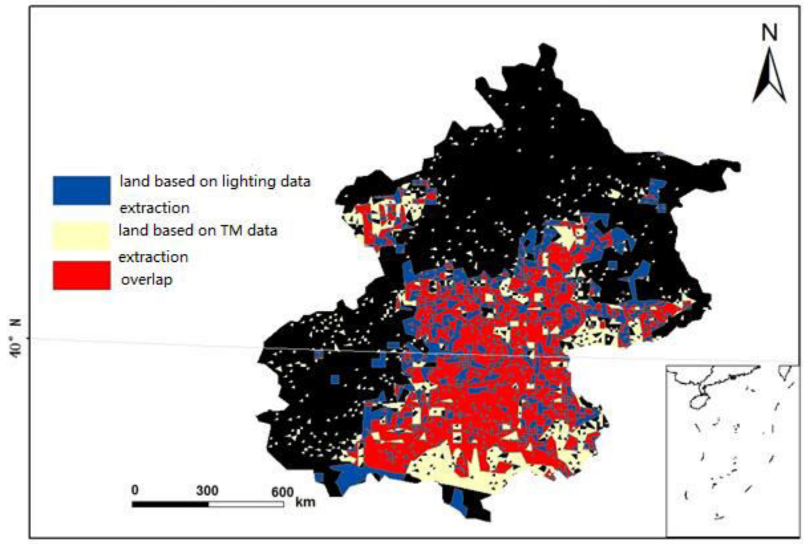


Fig. 4. Comparison of extraction results by light data and TM image

3.3 Provincial Carbon Emissions Calculation Results

Using the above methods, China's CO_2 emissions in 2000, 2005 and 2013 were respectively calculated. It can be seen from the calculation results that CO_2 emissions in various provinces in China are expanding constantly, with the values in the eastern provinces far exceeding those in the western provinces. The line graphs of CO_2 emissions in 2000, 2005, and 2013 are shown in Fig.5. It can be seen a rising trend of CO_2 emissions in China from 2000 to 2013. The emission volume grew from 4.30 billion tons in 2000 to 12.64 billion tons in 2013, with an average annual growth rate of 8.6%. From a global point of view, CO_2 emissions of China have undergone two major changes: from 2000 to 2005, the increase has been relatively rapid, with an average annual growth rate of 12.1%; from 2005 to 2013, the growth rate has slowed down, with an average annual growth rate of 6.5%.

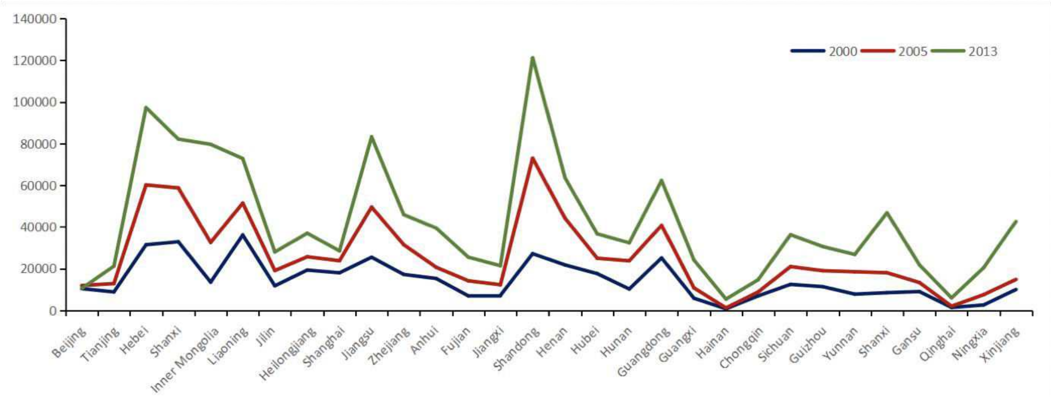


Fig. 5. Graph of CO_2 emissions in China in 2000, 2005 and 2013

3.4 Correlation Analysis of Energy Carbon Emission and Nighttime Light Brightness

In order to explore whether there is a correlation between nighttime light brightness and carbon emissions, a correlation analysis of provincial carbon emissions and provincial night light brightness was conducted. The fitted results shown in Fig.6 suggest a clearly linear relationship between the nighttime lighting data and the CO_2 emission statistics with R^2 moves between 0.62 and 0.72. These results are consistent with the conclusion that there is a linear relationship between night light data and CO_2 at the global level, national level, provincial level and some urban level.

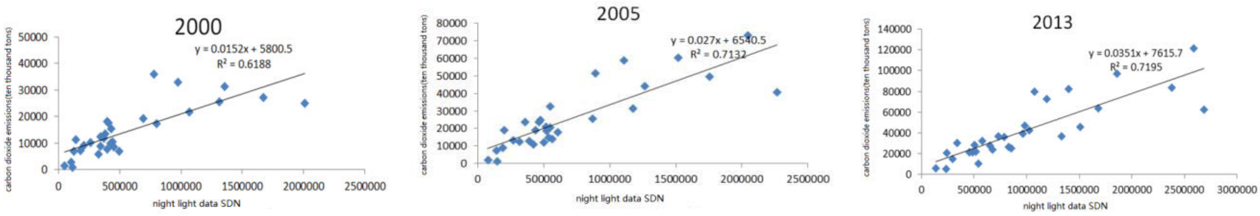


Fig. 6. Fitting relationship between the total value of light data at night and the CO_2 emission statistics

3.5 Municipal Carbon Emissions Results and Analysis

3.5.1 Municipal Carbon Emissions Results

According to the above fitting analysis, the provincial nighttime light brightness linearly correlates with the CO_2 emissions. Through provincial and municipal administrative division maps of China, zone statistics were applied to the nighttime lighting data, so we can obtain the statistics on the nighttime lighting data of more than 300 cities in China in 2000, 2005, and 2013. By using the municipal energy carbon emission model in formula 2, China's municipal CO_2 emission volume can be calculated.

The increase in carbon emissions in 2005 over 2000 and the increase in 2013 over 2005 are shown in Fig.7. At the city level, the total amount of CO_2 emissions had been continuously increasing from 2000 to 2013 as the urban area gradually expanded. China's CO_2 emissions grew from 11.91 million tons in cities in 2000 to 34.85 million tons in 2013, with an average annual growth rate of 8.6%. From 2000 to 2005, the total volume of CO_2 increased rapidly with an average annual growth rate of 12.2% followed by a steadily growth with an average annual growth rate of 6.5%. Comparing urban carbon emissions of different urban areas, the carbon emissions of different cities are not balanced. For example, the carbon emissions in the metropolitan areas of Beijing, Shanghai and Guangzhou are far beyond other cities. Shanghai emitted the most carbon among all the cities. In 2000, Shanghai's CO_2 emissions amounted to 204.73 million tons, and by 2013 it had reached 275.07 million tons, with an average annual increase of 5.41 million tons. As a global metropolis and the economic center of China, Shanghai has emitted far more CO_2 than other cities due to its rapidly industrial and economic development since China began to implement a series of economic policies on Shanghai in the last century.

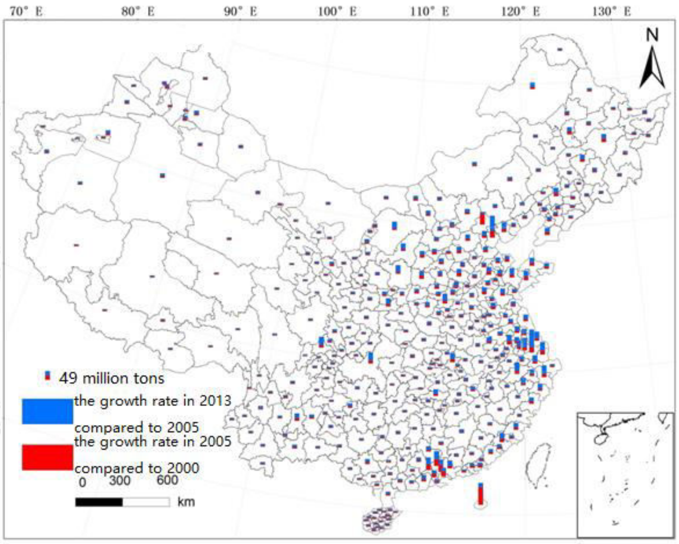


Fig. 7. Comparison of carbon emissions growth 2005 vs. 2000 and 2013 vs. 2005

From the perspective of regional heterogeneity, the CO_2 emissions were majorly concentrated in the eastern regions of China. After 2000, China's economic development began to switch towards the harmonious development in each region and therefore carbon emissions began to grow steadily in the eastern and the western region. The eastern region optimized its economic structure and devoted itself to improving the quality of development. At the same time, the economic growth rate and public policies in the central region are relatively stable and its carbon emissions have stabilized. For the western region, the carbon emissions have been relatively low. Since the beginning of the western development policy, the regional carbon emissions have begun to rise slowly over the period. Though the western economy has not grown rapidly due to insufficient funds and imperfect infrastructure, carbon emissions in Western China also increased in 2005 and 2013 compared to 2000. As for Northeastern China, since the 1990s, due to the gradual decline of the old industrial bases in the northeast, the gap between the northeastern region's economy and the developed eastern coastal regions has continuously expanded. Since 2003, after the country officially began to make important strategic decisions for the rejuvenation of the industries in that region, the CO_2 emissions in the northeastern China began to rise rapidly. It can be seen that the regional GDP is one of the factors influencing the total amount of carbon emissions in different regions.

In order to further analyze the temporal and spatial changes of CO_2 emissions in cities of China, the annual average growth of each city from 2000 to 2013 was calculated and classified. There are five types of energy sources of city CO_2 emissions all over China. The criteria for its classification are shown in Table 2, including slower growth type, slow growth type, medium speed growth type, fast growth type, and faster growth type. The final results showed that 9 cities are faster growth type and 17 cities are fast growth type, mainly concentrated in some eastern areas where the economy is comparatively developed (Fig. 8). In addition, 89 cities are classified as slow growth type, and 211 cities are classified as slower growth type, mainly concentrated in the less developed regions such as the western region and the northeastern and central regions (Fig. 8). It can be concluded that the growth rate of total CO_2 emissions in different regions of China is closely related to its economic development speed and degree of development.

Table 2 Classification of CO_2 Growth Types

Type of Growth	Slower Growth Type	Slow Growth Type	Medium Speed Growth Type	Fast Growth Type	Faster Growth Type
Annual growth (10 thousand tons)	0-150	150-250	250-350	350-500	>500

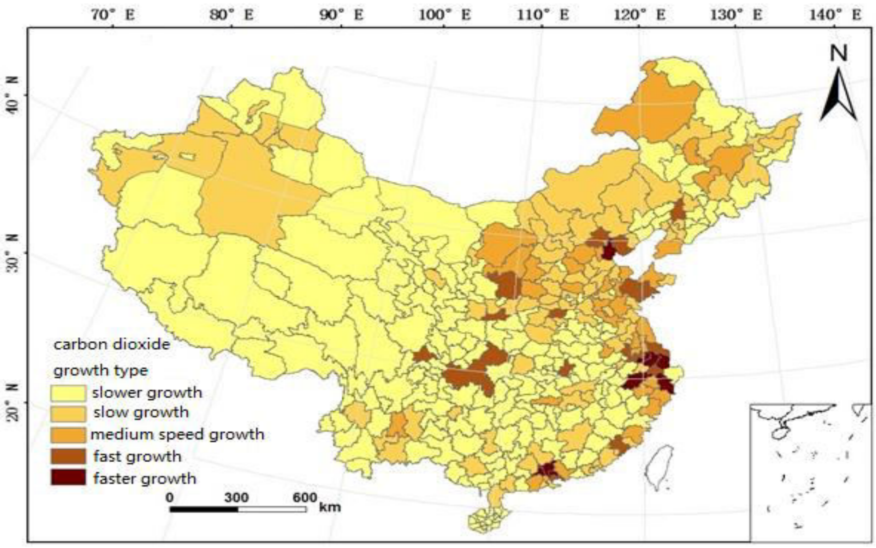


Fig. 8. Types of total CO_2 emissions growth over the period 2000-2013

3.5.2 Analysis of Per Capita Carbon Emissions

From the above analysis of the total amount of carbon emissions, it can be seen that due to differences in the status, policies, and industrial development structure of economic development in different regions during different time periods in the country, the total amount of CO_2 emissions in the four major economic zones, the eastern, central, western, and northeast regions of China, present different characteristics. The eastern region, the most densely populated and most economically developed region, has released the most CO_2 emissions.

Further analysis on the per capita carbon emissions of the four major economic regions reveals that between 2000 and 2013 per capita carbon emissions are on the rise. Due to better economic development in the eastern region, the higher standard of living, and the greater total amount of energy consumption, the per capita carbon emissions are slightly higher. Because the northeastern region is dominated by heavy industries, the per capita carbon emission level is relatively higher for its low energy efficiency and large consumption. In some central regions, due to the much smaller population and the larger energy consumption, the per capita carbon emissions are even higher than in the eastern region. Per capita carbon emissions from 2000 to 2013 is shown in Fig.9. Per capita carbon emission growth rate was 11.8% from 2000 to 2005, and 5.2% from 2005 to 2013. The calculation is shown in Equation (4).

$$\text{Per capita carbon emissions} = \text{Total carbon emissions} / \text{Total population} \quad (4)$$

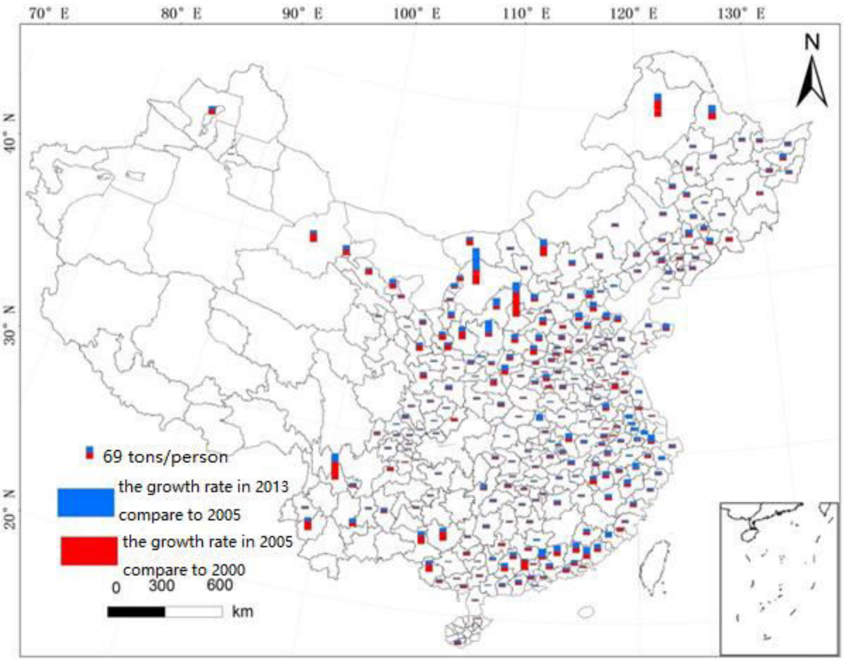


Fig. 9. Per Capita Carbon Emission Growth

4. Discussions

By using DMSP/OLS night light remote sensing data to estimate city-level energy carbon emissions, the research and methodology in this paper not only overcomes the shortage of energy carbon emission statistics in Prefecture-level cities, but also unifies the methods of carbon emission assessment at provincial and municipal levels, which can help in formulating more reasonable carbon emission reduction policies. There are few studies on energy carbon emissions using DMSP/OLS night lighting data, most of which are at the global or national level and a few at the provincial or municipal level. The methods for estimating carbon emissions for municipal energy are still in their infancy but provide a useful for reference. An important next step would be to validate the estimated results with actual carbon emissions data on urban energy consumption.

5. Conclusions

In this paper, we constructed an estimation model for city carbon emission to overcome the difficulty of collecting statistical data at the municipal level in China. The main conclusions can be summarized as follows:

1. The results show that the developed land in China continued to expand from 2000 to 2013, with an annual growth rate of 13.4% from 2000 to 2005 and 15.9% from 2005 to 2013.

2. It is found that there was a clearly linear correlation between nighttime lighting of cities and CO_2 energy, with the R^2 at 0.62 in 2000, 0.71 in 2005 and 0.72 in 2013.

3.By constructing a city-level carbon emission inversion model, city-level CO_2 emissions were obtained. In general, during 2000 to 2013, the CO_2 emissions were on the rise in China. It grew from 4.30 billion tons in 2000 to 12.64 billion tons in 2013, with an average annual growth rate of 8.6%. From 2000 to 2005, the growth rate was rapid with an average annual growth rate of 12.2%. From 2005 to 2013, the growth rate slowed down and became less volatile to 6.5%. The growth rate of carbon emissions varied in different regions of China. Faster growth types and fast growth types were mainly concentrated in the more economically developed regions in eastern China. In conclusion, the regional distribution of carbon emissions is characterized by “high concentration in the east and low concentration in the west”. In addition, carbon emissions per capita were also increasing year by year. The eastern region was far higher than the western region.

4. The annual average growth rate of cities from 2000 to 2013 can be divided into 5 types. The results showed that there are 9 faster-growing cities and 17 fast-growing cities, mainly concentrated in some eastern developed areas. In addition, 89 slow-growing cities and 211 slower-growing cities are found mainly in the less developed regions such as the western

region, the northeastern and central regions. The growth rate of total CO_2 emission in different regions of China is closely related to the economic development speed and degree of development of those regions.

The results have important implications for the emission reduction policy in China. In the heavy industrial cities such as cities in the western and northeastern provinces, the focus of emission reduction should be on the improvement of energy efficiency and capacity utilization. For cities in the eastern and central regions that are dominated by light industry, the focus of their emission reduction should be on the adjustment of the structure of the industry.

Author declarations

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Author Statement

The corresponding author is responsible for ensuring that the descriptions are accurate and agreed by all authors.

Li Wang designed the study, developed the methodology, and wrote the manuscript.Huanguang Deng was responsible for the revision and retouching of the manuscript. Niyu Zhang performed the experiment and performed the data analysis. Peifa Wang and Fei Yang offered part of data and provided guidance. John J. Qu provided some guidance and revise opinion of the paper.Xiaoxue Zhou provided direction and formulated the original problem.

Conflicts of interest

It should be understood that none of the authors have any financial or scientific conflicts of interest with regard to the research described in this manuscript.

Ethics declarations

Our research do not have any animal experiment and do not do harm to human beings and society.

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