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ANALYSIS OF CO_2 EMISSIONS MANAGEMENT PERFORMANCE IN CHINA AT SUB-PROVINCE LEVEL

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Abstract

Sub-province (prefecture-level) regions are more fundamental and flexible in carbon mitigation and policy implementation in China compared to provinces and counties, due to their more manageable area than provinces, and more powerful governing capacity by means of regulations and standards than counties. Using the EDGAR database and prefecture boundary data, CO_2 (carbon dioxide) emission management performances at the prefecture level in China were investigated using statistical analysis. The results demonstrate that the spatial pattern of China's CO_2 emissions was mainly concentrated in certain key prefectures. The top ten prefectures in terms of per capita emissions are all concentrated along the coal mining belt in north China. Half of the prefectures (46%) in China have contributed more than 80% of total emissions, and roughly one third of the population lives in prefectures where annual per capita emissions are above the national average emissions level (5.7 ton CO_2). Clustering analysis show that prefectures in China can be categorized into 6 groups, and half of the prefectures were in the low emission and low economy group. It is urgent for the prefectures in this group to make a low carbon transition so as to avoid the fate of high emission development. The implication of these findings for policymakers is that prefectures should be the focus of future strategies for low carbon development rather than provinces, and the selection of low carbon pilots need be based on the type of development, emissions intensity and their representativeness of certain category of prefectures.

Key words: CO_2 emissions, low carbon development, prefectures

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1. Introduction

China is a fast-growing economy and a major force in anthropogenic carbon emissions and their efforts for mitigation. From 2000 to 2012, China's CO_2 (carbon dioxide) emissions from fossil fuels increased at an annual rate of 9%, and surpassed the U.S. in 2008 to become the world's largest emitter of anthropogenic carbon dioxide (BP, 2013). While China's leading share of global CO_2 emissions has been recognized, previous studies mainly focused on estimation and analysis at the national level (Kong and Wei, 2017; Peters et al., 2007; Tan et al., 2011; Yang et al., 2017; Zhang et al., 2009a; Zhang et al., 2009b; Zhang et al., 2012) and the provincial level (Auffhammer and Carson, 2008; Han et al., 2015; Liu, 2013; Wang et al., 2013; Zhang et al., 2013; Zhao et al., 2012). There is a lack of detailed analysis at finer spatial scale. In China provinces are subdivided into prefecture-level regions formerly termed as prefecture-level cities and prefectures (including prefectures, leagues and autonomous prefectures).

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Prefecture-level regions constitute the second level of the administrative structure, ranking below provinces and above counties, and contain multiple districts, county level cities and counties.

Considering the relatively manageable area (average land area of 27,500 km^2 versus average land area of 310,000km^2 of provinces), and more powerful governing capacity by means of regulations and standards than counties, prefecture-level regions are regarded to be more fundamental and flexible in carbon mitigation and policy implementation compared to provinces and counties (CSCIEAS et al., 2011, 2012). That is why China places significant efforts in CO_2 emissions reduction in prefecture-level regions (especially prefecture-level cities) and recognizes it as the major targets for CO_2 reduction (CSCIEAS et al., 2011, 2012; IEAS et al., 2014). The central government of China launched low-carbon pilots in 2010 in 2 municipalities directly under the central government (MDUCG), 6 prefecture-level cities (Shenzhen, Xiamen, Hangzhou, Nanchang, Guiyang, and Baoding) and 5 provinces to try, explore, and demonstrate a low carbon development pathway for China. A large number of research programs concerning city carbon emissions and low carbon city in China are actually carried out at prefecture-level cities (Li et al, 2010; Liu et al, 2010; Chun et al., 2010; Hoornweg et al., 2011; Geng et al., 2011; Sugar et al, 2012; Wang and Chang, 2018). Although in Chinese there is a word “city” in the name of prefecture-level city, they are more like regions rather than city in the international sense of the term (i.e. a large continuous urban settlement) (Zhang et al, 2011a; Zhang et al, 2014; Cai and Zhang, 2014).

China lacks statistical data of fossil fuels consumption at the prefecture-level. This data deficiency has already impeded an accurate understanding and evaluation of CO_2 emissions and low carbon development status of local regions in China. This data gap also limited emission performance comparisons between prefectures and emission benchmark-setting for prefectures. It inhibited prefecture-level allocations of CO_2 emissions allowances from higher level of government, both at the provincial and national level.

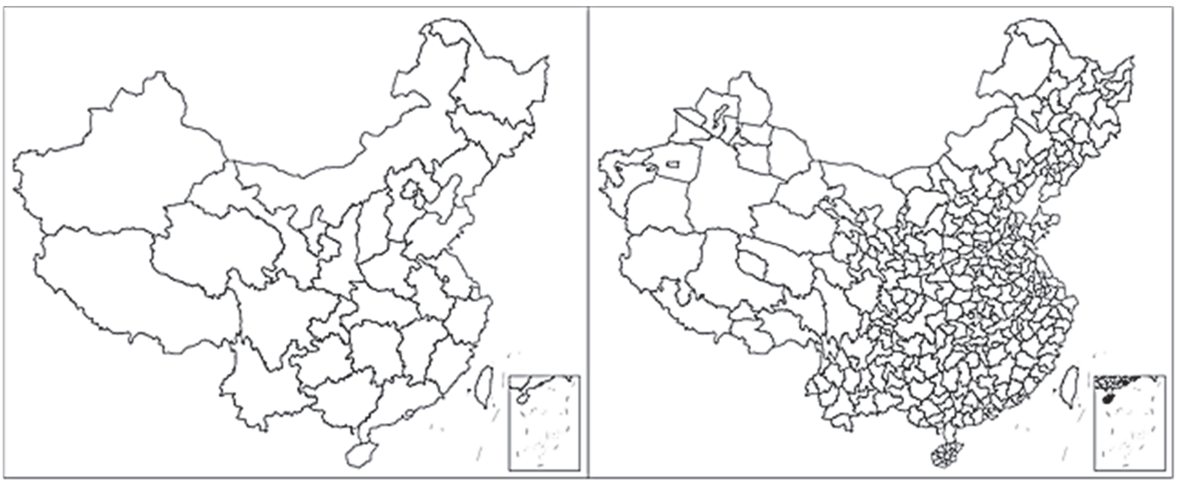
The general patterns and characteristics of CO_2 emissions at the prefecture level in China are unclear and urgently need in-depth collation and analysis. In this study, for the first time in China, high-resolution gridded CO_2 emissions data from the Emissions Database for Global Atmospheric Research (EDGAR) were used and combined with prefecture vector boundary data to discuss and explore the CO_2 emissions at the prefecture level. The main objectives of this article are to: 1) analyze the spatial characteristics of CO_2 emissions in China and their geo-correlation with the distribution of prefectures; 2) analyze the general characteristics of CO_2 emissions of prefectures and its correlation with the economy and population; 3) carry out cluster analysis on the prefectures in China to distinguish the characteristics of the different categories of the prefectures; 4) propose policy recommendations concerning CO_2 emissions reduction at the prefecture level.

2. Data and methodology

2.1. Prefectures

There are 345 prefecture-level regions in China in 2010. Considering the spatial integrality of our analysis, we include 4 MDUCGs (Beijing, Shanghai, Tianjin and Chongqing) in our analysis to fully cover the whole area of China. Actually, MDUCGs have similar administrative structures (contain counties and districts) and comparable land size as prefecture-level regions. Therefore, there are 349 units in our analysis (Fig. 1) and we call these 349 units as prefectures thereafter.

Taiwan and the Special Administrative Regions of Hong Kong and Macao are not considered in this study. The prefectures vector boundary data are from National Administration of Surveying, Mapping and Geoinformation of China (http://www.sbsm.gov.cn) and National Geomatics Center of China (http://nfgis.nsdi.gov.cn).



(a) (b)

Fig. 1. Boundaries of provinces (a) and prefectures (b) in China *Note: There is no available prefecture boundary vector data of Taiwan*

2.2. CO_2 emissions data

The CO_2 emissions data discussed and analyzed in this study were directly derived from EDGAR. The EDGAR is a joint project of the European Commission Joint Research Centre and the Netherlands Environmental Assessment Agency, and provides data on global anthropogenic emissions of GHGs (JRC/PBL, 2013).

The EDGAR database is so far the highest spatial resolution dataset publically available, and includes the near 10-km spatial resolution CO_2 emissions dataset of China. EDGAR calculates the CO_2 emissions conforming to the methodology and emission source classification of IPCC guidelines (IPCC, 2006). Emissions for a country are calculated on an annual basis and sector wise, by multiplying the activity data with emission factors. The activity data are from International Energy Agency statistics for OECD and non-OECD countries, and the emission factors are from the IPCC guidelines. We only considered the emissions from the Energy activities and industrial Processes (non-combustion).

Emissions are allocated on a spatial grid of 0.1 degree to provide gridded emissions dataset. The EDGAR dataset use point/line emission sources, population density grids and land use data at various resolutions as spatial proxies to finish the gridded CO_2 emissions data. EDGAR only counted the direct CO_2 emissions. Therefore, CO_2 emissions analysis of prefectures in this article only consider the direct CO_2 emissions and do not include the indirect emissions that occur outside the prefectures' boundary as a result of activities that occur within the prefectures. Extensive studies have been conducted based on the EDGAR database and have proved its value and reliability (Alonso et al., 2010; Marland et al., 1999; Ohara et al., 2007; Parrish et al., 2009). Cai (2011) has analyzed the CO_2 emissions discrepancies between spatial aggregated data from EDGAR and data calculated from official energy statistical data at the provincial level in China. The EDGAR dataset still has uncertainties in spatial accuracy, although many works have tested its quality and proved its values. Overall, the EDGAR data is quite consistent with China's provincial energy data. The integrity of this dataset provides more consistent and comparable results when applied at the prefecture level. EDGAR gridded data combined with Chinese prefecture GIS vector data (Fig. 1) can be used to estimate CO_2 emissions of prefectures in China. Based on the GIS spatial analysis platform, the sum of CO_2 emissions of all grid cells that fall into each of geographical boundary of prefectures was calculated by the *Zonal Statistics tool*. If the grid cell spatially overlays more than one prefecture boundary, its emissions will be assigned to the prefecture that covers the largest part of that grid cell.

The base year of our analysis is 2008. Population and economic statistical data of prefectures in 2008 were derived from *China City Statistical Yearbook 2009* (USESD, 2010).

2.3. Analytic methods

We adopt Pearson correlation coefficients to determine to what extent prefectures' CO_2 emissions are associated with social and economic activity. The paired *t*-test (2-tailed) is used to establish if the correlation coefficient is significantly different from zero. The correlation analysis is based on SPSS software. Clustering analysis was operated on 349 prefectures with two variables, CO_2 emissions per capita and GDP per capita.

The Self-Organizing Feature Maps (SOM) was adopted as the clustering method. The SOM is trained using unsupervised learning to produce low dimensional data. The SOM method has strong unsupervised learning ability and nonlinear solving ability, which can best meet the clustering principle: i.e., maximize differences inter-groups and minimize differences intra-group, and avoid subjectively group number setting (Kohonen, 1990; Giraudel and Lek, 2001). The SOM analysis was implemented based on MATLAB software.

3. Results

3.1. General characteristics of prefectures'CO_2 emissions in China

The overall spatial pattern of CO_2 emissions of China in 2008 can be seen in Fig. 2. Along China's population Huhuanyong line (traditional population demarcation line in China), CO_2 emissions can be divided into two parts, east and west. The CO_2 emissions of grid cells in the eastern region are obviously higher than that of grid cells in the western region. In the eastern region, the CO_2 emissions in Shanghai, Beijing, Tianjin, Guangzhou, Zhengzhou, Chengdu, Chongqing, Wuhan, Xi'an and Shenyang were obviously higher than others. The spatial pattern of CO_2 emissions was significantly influenced by the presence of certain prefectures. The geographical boundaries of provinces do not indicate any marked tendency of the spatial distribution of CO_2 of China. Grids with high value of CO_2 emissions were centered by key prefectures such as Beijing, Shanghai and Guangzhou.

Fig. 3 illustrates the prefectures' CO_2 emissions and spatial pattern. Generally speaking, the prefectures in the eastern part of China mostly showed high total CO_2 emissions, especially on the North China Plain. According to amount of CO_2 emissions, Shanghai, Tianjin, Beijing, Chongqing, Guangzhou, Xuzhou, Taiyuan, Suzhou, Yangzhou and Zhengzhou in that order ranked as the 10 largest emitters. Annual CO_2 emissions of the top four prefectures all exceed 100 million tons (Mt) (Fig. 4). Figs. 5-6 shows per capita CO_2 emissions and its spatial distribution of prefectures, which is significantly different from Figs. 3-4.

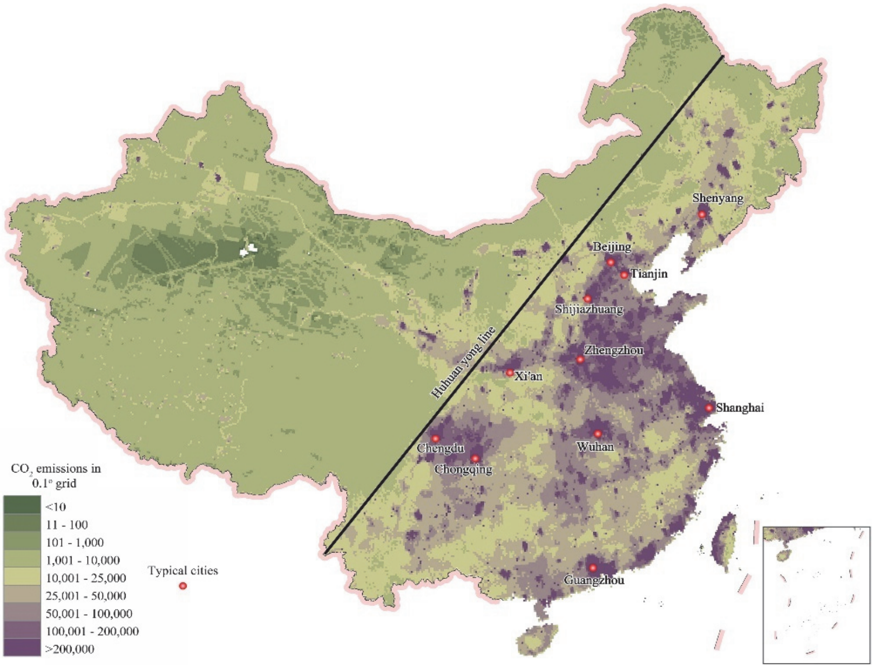


Fig. 2. Spatial distribution of CO_2 emissions in China on 0.1° grid resolution, 2008
Note: The data are from The EDGAR database

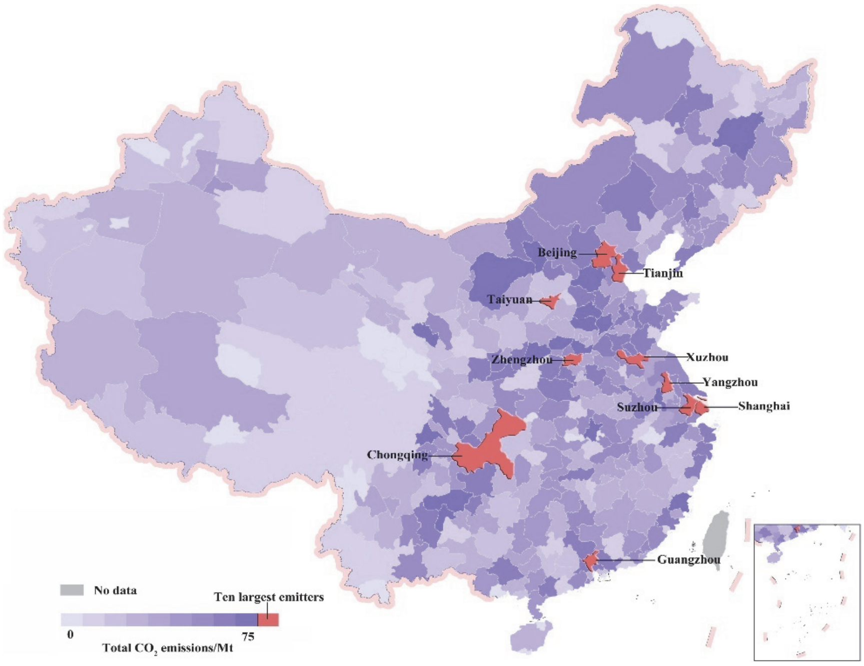


Fig. 3. Prefectures' total CO_2 emissions in China in 2008

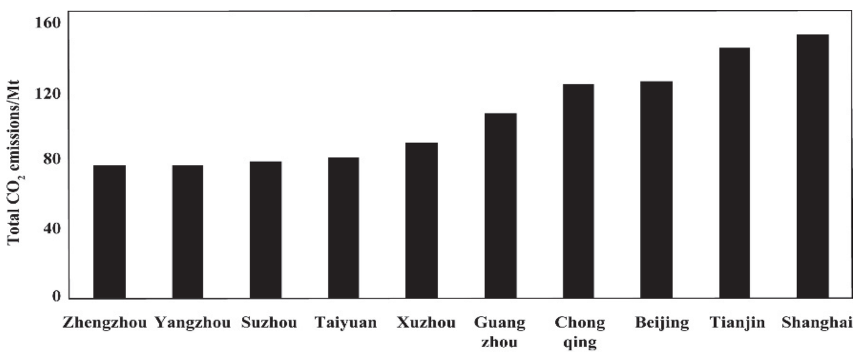


Fig. 4. Top ten prefectures in terms of total CO_2 emissions in China in 2008

The per capita emissions map shows no notable differences between the west and east region, whereas it highlights north China as the hotspot regions in terms of per capita emissions. The top 10 prefectures in per capita emissions, i.e., Alashan, Wuhai, Erdos, Jiyuan, XilinGol, Shizuishan, Jincheng, Hohhot, Shuozhou and Taiyuan, are all concentrated in north China. Among these prefectures, five (Alashan, Wuhai, Erdos, XilinGol, Hohhot) belong to the province-level Inner Mongolia autonomous region, three (Jincheng, Shuozhou, Taiyuan) belong to Shanxi province, and the other two prefectures, Jiyuan and Shizuishan, belong to Henan province and Ningxia autonomous region, respectively. The top ten prefectures are located along the Alashan-Wuhai-XilinGol line, which is the key belt for coal mining in China. The coal resources boost coal-based heavy industry (e.g., coal mining, coal washing, coal fired power generation, coke production), which dominates the industrial structure of this region. This energy and industrial structure consequently results in large volumes of CO_2 emissions. Meanwhile, this region is also an important ecotone (transition area between arid and semi-arid systems) of China, with fragile ecological condition and limited carrying capacity. The ecological conditions lead to low population density in this region. High CO_2 emissions with low population yield high per capita CO_2 emissions. The cumulative prefecture number curve (Fig. 7) expresses the magnitudes of prefectures' CO_2 emissions and their proportions in total emissions. There are 69 prefectures with emissions larger than 35 Mt, accounting for half of the total emissions, 159 prefectures with emission larger than 18 Mt, accounting for 80% of the total emissions, and 211 prefectures with emissions larger than 11 Mt, accounting for 90% of the total emissions. This phenomenon indicates that CO_2 emissions in China are dominated by large prefectures, with less than half of the prefectures (46%) generating 80% of the emissions and the remaining 20% of the emissions shared by the other half of the prefectures (54%). Fig. 8 highlights the prefectures' CO_2 emission from the perspective of population.

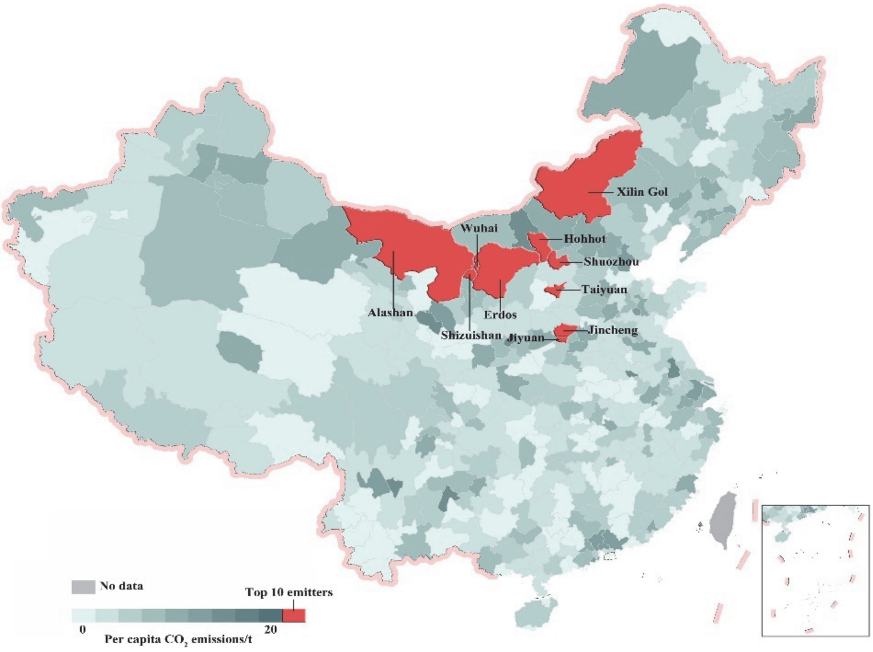


Fig. 5. Prefectures' per capita CO_2 emissions in China in 2008

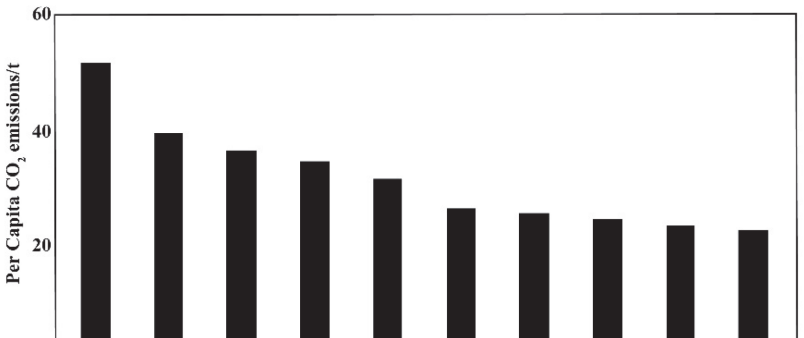


Fig. 6. Top ten prefectures in terms of per capita CO_2 emissions in China in 2008

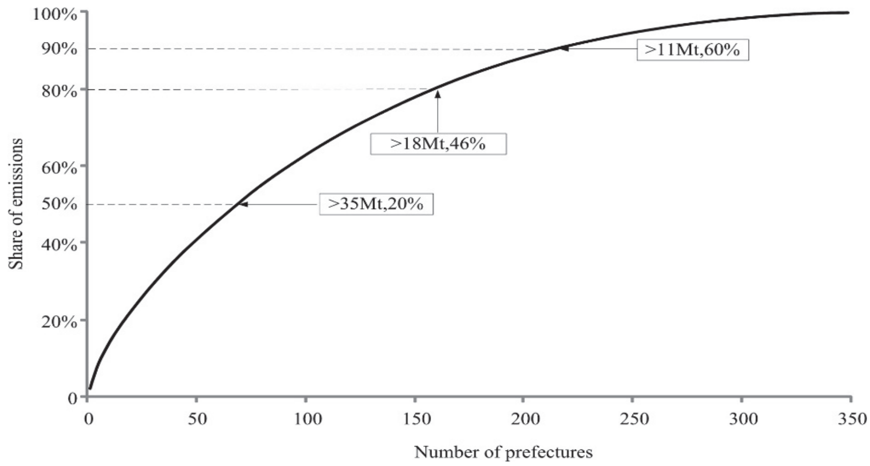


Fig. 7. Accumulated emissions of prefectures
Note: The percentage refers to the ratio of number of prefectures to the total number of prefectures

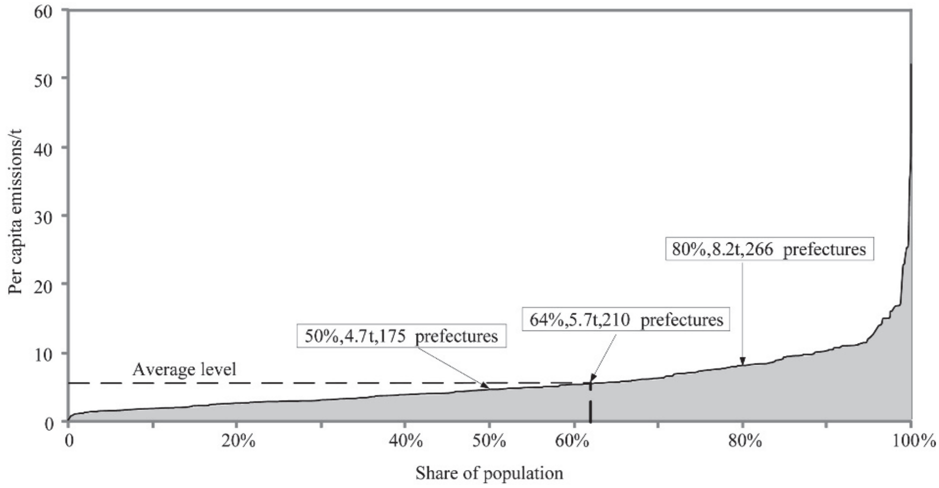


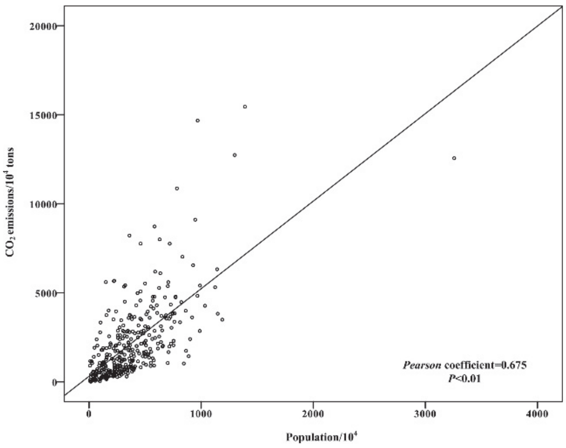
Fig. 8. Per capita emission and population share of prefectures.
Note: The percentage refers to the ratio of population in the prefectures to the population in all the prefectures. The gray area represents the relative amount of total CO_2 emissions

The curve in Fig. 8 shows a sharp upward result at the per capita emission level of 10t, after gradual increase from 0 to 90% in the prefectures' population share in total population. This means only few prefectures have high level of per capita emissions and there are significant differences between these few prefectures. The per capita CO_2 emission of China was 5.7t in 2008. Roughly 64% of the population lives in prefectures with average emissions no more than this level, and half of the population (in 175 prefectures) lives in prefectures with average emissions lower than 4.7t. This implies that the emissions are concentrated in a relatively small proportion of the population in a few prefectures. The aggregated emissions from the top ten prefectures in terms of total CO_2 emissions (Fig. 4) accounted for 14% of total emission of China.

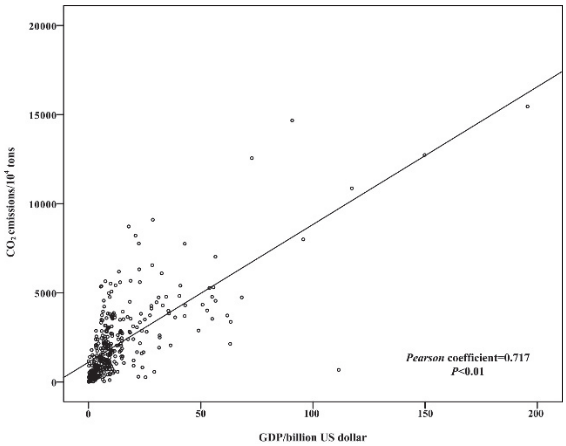
3.2. Correlation analysis between prefectures' CO_2 emissions and population, economy

Fig. 9 shows the results of correlation analysis among China's prefectures' CO_2 emissions and prefectures' population and GDP. Both Pearson correlation coefficients have passed the test of significance (0.01). This proves that population and economic activities may be the important driving factors of prefectures' CO_2 emissions in China. The previous analysis also demonstrates that the hotspots of China's CO_2 emissions are located in key prefectures with dense population and intensive economic activities. The correlation coefficient of CO_2 emissions with GDP is higher than correlation coefficient of CO_2 emissions with population, which is consistent with the conclusion of Doll et al. (2000). This demonstrates that the driving force of prefectures' CO_2 emissions is stronger from economic activities than from population growth.

Fig. 10 shows the result of correlation analysis between China's prefectures' population density and per capita CO_2 emissions. There is a weak (Pearson coefficient=0.093, $P<0.1$) positive relationship between population density and per capita CO_2 emissions. The possible underlying reason is that the per capita incomes were relatively higher in big prefectures with dense population, such as Shanghai and Beijing, and therefore, the per capita fossil fuel consumption would be higher in those affluent prefectures than in other prefectures.



(a)



(b)

Fig. 9. Correlation between prefectures' CO_2 emissions and population (a) and GDP (economy) (b) in China (GDP is calculated based on nominal GDP of China in 2008; the official exchange rate between US dollar and RMB in 2008 is 1:6.94)

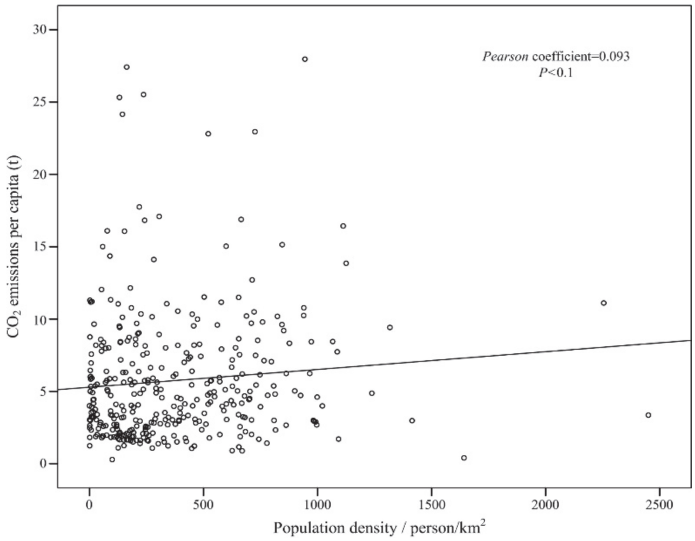


Fig. 10. Correlation between prefectures' population density and per capita CO_2 emissions

3.3. Clustering analysis on CO_2 emissions of prefectures

Differentiated policies based on different regions characterized by CO_2 emissions and economic development is essential for regional development and CO_2 reduction. Most studies on China's CO_2 emissions clustering have been carried out at the provincial level (Wang et al., 2011; Xiao et al., 2011; Zhang et al., 2011b), due to convenient data availability and accessibility. But each of the Chinese provinces covers an enormous area and is internally imbalanced in economic development and CO_2 emissions within the province.

According to the analysis above, the spatial pattern of China's CO_2 emissions is more evident at the next level down, the prefecture level regions, rather than provinces, so policy recommendation based on prefecture level is much more valuable and reasonable. The results of clustering analysis can be seen in Table 1 and Fig. 11. The output of optimal grouping is 6 groups (initial set is 4-10 groups). All clustering results passed *F*-test ($p<0.01$). It is worth noting that the GDP per capita (thousand US dollar) is merely the proxy of the intensity of economic activity, rather than the quality of life and welfare of citizens.

Therefore in Table 1, for some resource-based prefectures and industrial prefectures, the higher per capita GDP does not fully reflect the higher quality of life. However, per capita GDP is still a very important indicator for economic development.

According to the clustering analysis, prefectures can be categorized into 6 groups: the first group is featured with *high emissions, high economy*. There are 8 prefectures in this group in China, including Beijing, Shanghai and Guangzhou. The second group is *Relatively-high emissions, relatively-low economy* group, and is characterized by high CO_2 emissions per capita but low GDP per capita. This group consists of 89 prefectures, which are mainly province level capital prefectures and other major prefectures in their own provinces.

Table 1. The features of prefecture-groups of China

Groups	*Average CO_2 emissions per capita (ton)*	*Average GDP per capita (thousand US dollar)*	*Numbers of prefectures*	*Typical prefectures*
High emissions, high economy	12.14	14.74	8	Beijing, Shanghai
Relatively-high emissions, relatively-low economy	8.46	4.29	89	* Hangzhou, Guiyang
Low emissions, high economy	2.95	18.99	6	* Shenzhen, * Xiamen
High emissions, relatively-low economy	20.38	5.23	33	* Tianjin,Taiyuan
Relatively-high emissions, low economy	5.07	2.67	88	* Chongqing, Baoding
Low emissions, low economy	2.35	2.09	125	* Nanchang,Guangyuan

*Note: Emissions means per capita CO_2 emissions, economy means per capita GDP; * means low carbon pilots. The GDP is calculated based on nominal GDP of China in 2008. The official exchange rate between US dollar and RMB in 2008 is 1:6.94*

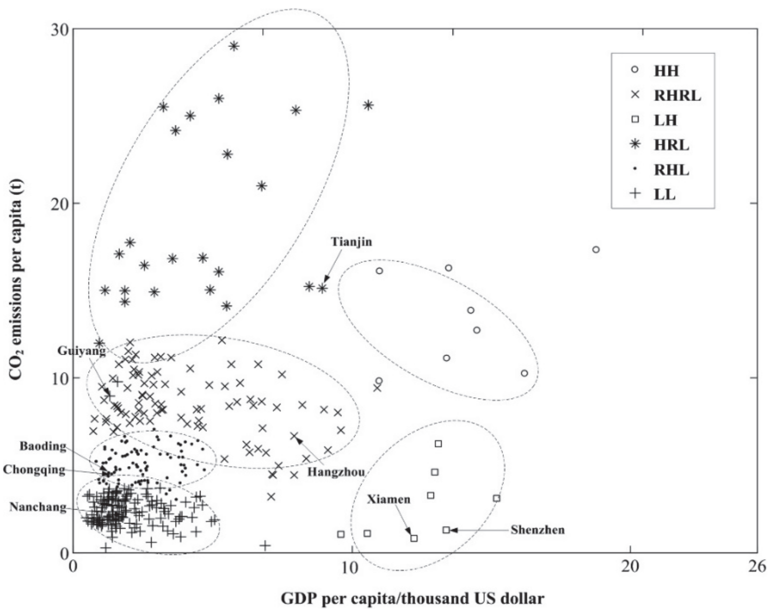


Fig. 11. Classification of prefectures of China based on CO_2 emissions and GDP. Note: HH: High emissions, high economy; RHRL: Relatively-high emissions, relatively-low economy; LH: Low emissions, high economy; HRL: High emissions, relatively-low economy; RHL: Relatively-high emissions, low economy; LL: Low emissions, low economy. The prefectures indicated in the figure are low carbon pilots. The GDP is nominal GDP of China in 2008. The official exchange rate between US dollar and RMB in 2008 is 1:6.94

The third group is the *low emissions, high economy* group, and is characterized by low CO_2 emissions but high GDP per capita. Prefectures in this group are the ideal model for low carbon development. Because they exemplify the feasibility for local regions to reduce CO_2 emissions while keep being on a high economic level. However these prefectures are mainly the eastern coastal prefectures such as Shenzhen, Xiamen etc., in which the service sector is the main component of the economy. The fourth group is the *high emissions, relatively-low economy* group, and is characterized by high CO_2 emissions per capita, and relatively low GDP per capita. Most of the prefectures in this group are industrial prefectures. The fifth group is the *relatively-high emissions, low economy* group. The CO_2 emissions level is quite high, but the GDP per capita is low in this group. There are 88 prefectures in this group. The sixth group is the *low emission and low economy* group. The CO_2 emissions per capita and GDP per capita are both low. The number of prefectures in this group is 125.

Clustering analysis indicated that half of the total prefectures in China were in the situation of low emission and low economy. According to the previous correlation analysis between prefectures' CO_2 emissions and GDP, if China develops its economy on the current track, prefectures are very likely to follow the pathway of high emission and high economy. Beijing and Shanghai and other typical prefectures are representative of such a development model with high emission and high economy. In addition, there are some prefectures with special traits, for instance resources-based and industry-oriented prefectures. Erdos and Baotou are resource-based prefectures with high GDP per capita and high CO_2 emissions per capita because the economic development and CO_2 emissions are largely driven by resource extraction and processing. Wuhai and Taiyuan are industrial prefectures: their high emissions are due to the imbalanced economic structure, dominated by heavy industry.

5. Conclusions and policy implications

The spatial pattern of China's CO_2 emissions indicated that emissions were mainly concentrated in certain key prefectures. Provinces in China are internally imbalanced in terms of economic development and CO_2 emissions. Key prefectures rather than provinces mainly influence the spatial pattern of China's CO_2 emissions. Therefore, the prefectures should be the focus of future strategies and policies for low carbon development. The rationale and process of the policy-making should mainly be based on prefecture scale rather than provincial scale. Therefore, an accurate, consistent, timely energy statistical system for all the prefectures is very urgent and crucial for the decision making.

The statistical capacity building on prefectures is also essential for both research in the area of regional CO_2 emissions and mitigation practices. China's CO_2 emissions are dominated by large prefectures, with less than half of the prefectures (46%) generating 80% emissions. The top ten prefectures in terms of total emission are prefectures with dense population and intensive economic activities. The top ten prefectures in terms of per capita emissions are all concentrated along the coal mining belt in north China. Roughly 64% of the population lives in prefectures whose per capita emissions are under national average emissions level (5.7t). Therefore, the focus of carbon emission reduction should be mainly directed to large prefectures. Furthermore, high carbon intensive industrial prefectures, such as coal-based industrial prefectures in north China, should draw attention from policy makers. It is urgent for them to make a low carbon transition so as to avoid the fate of high emission development.

We also found significant correlations between population, the economy and CO_2 emissions at prefecture level in China, and the economic development is the main driving force of CO_2 emissions. Unfortunately, there is no pilot prefecture launched by the central government coming from the *high emission, high economy* group. The prefectures from *low emission, high economy* group accounted for 33% of pilot prefectures, which is obviously higher than prefectures from other groups. This indicates that China tried to start a low carbon prefecture strategy from prefectures with good economic conditions and low CO_2 emissions. There are less pilot prefectures from *low emission and low economy* group, which represent the general carbon development level of prefectures in China. In addition, there is a lack of industrial prefectures as pilot prefectures, even though these account for a big share of prefectures in China. Low carbon development in China is considered as a process of low carbon transformation for all prefectures: each prefecture or every type of prefecture should build up their own pathway of low carbon development. Our findings demonstrated that the selection of pilot prefectures should consider representativeness. According to our analysis and knowledge, it is suggested that policy makers may best select low carbon pilots based on type of development and emissions with consideration of representativeness.

Acknowledgments

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