

# China's Carbon Emissions Report 2016:


## Regional Carbon Emissions and the Implication for China's Low Carbon Development

Zhu Liu



HARVARD Kennedy School  
**BELFER CENTER**  
for Science and International Affairs

**REPORT**  
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# The Environment and Natural Resources Program (ENRP)

The Environment and Natural Resources Program at the Belfer Center for Science and International Affairs is at the center of the Harvard Kennedy School's research and outreach on public policy that affects global environment quality and natural resource management. Its mandate is to conduct policy-relevant research at the regional, national, international, and global level, and through its outreach initiatives to make its products available to decision-makers, scholars, and interested citizens.

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**Zhu Liu**. Dabo Guan, Wei Wei, Steven J. Davis, Philippe Ciais, Jin Bai, Shushi Peng, Qiang Zhang, Klaus Hubacek, Gregg Marland, Robert Andres, Douglas Crawford-Brown, Jintai Lin, Hongyan Zhao, Chaopeng Hong, Tom Boden, Kuishuang Feng, Glen Peters, Fengming Xi, Junguo Liu, Yuan Li, Yu Zhao, Ning Zeng, and Kebin He. Reduced carbon emission estimates from fossil fuel combustion and cement production in China. *Nature* 524, 335-338 (2015).

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**Zhu Liu**, Soeren Linder, Yong Geng, Bing Xue, Fengming Xi, Ying Pan, TianZhu Zhang, Tsuyoshi Fujita. Features, trajectories and driving forces for energy-related GHG emissions from Chinese mega cites: The case of Beijing, Tianjin, Shanghai and Chongqing. *Energy* 37, 245-254 (2012).

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**Zhu Liu**, Yong Geng, Soeren Linder, Hongyan Zhao, Tsuyoshi Fujita, Dabo Guan. Embodied energy use in China's industrial sectors. *Energy Policy* 49, 751-758 (2012).

Dabo Guan, **Zhu Liu**, Yong Geng, Soeren Lindner, Klaus Hubacek. The gigatonne gap in China's carbon dioxide inventories. *Nature Climate Change*, 672-675 (2012).

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A man rides a bicycle along a road on a heavily polluted day in Beijing, Sunday, Nov. 29, 2015. (AP Photo/Andy Wong)



# Executive Summary:

Climate change driven by anthropogenic carbon emissions is one of the most serious challenges facing human development. China is currently the world's largest developing country, primary energy consumer, and carbon emitter. The nation releases one quarter of the global total of carbon dioxide (9.2 Gt CO<sub>2</sub> in 2013), 1.5 times that from the US. Nearly three-quarters (73%) of the growth in global carbon emission between 2010 and 2012 occurred in China. Without mitigation, China's emissions could rise by more than 50% in the next 15 years. Given the magnitude and growth rate of China's carbon emissions, the country has become a critical partner in developing policy approaches to reduce global CO<sub>2</sub> emissions.

China is a country with significant regional differences in terms of technology, energy mix, and economic development.<sup>1</sup> Understanding the characteristics and state of regional carbon emissions within China is critical for designing geographically appropriate mitigation policies, including the provincial cap and trade system that is projected to be launched in 2017. In this study, I summarize the key features and drivers of China's regional carbon emissions and conclude with suggestions for a low carbon policy for China.

The principal findings are:

(1) Provincial aggregated CO<sub>2</sub> emissions increased from 3 billion tons in 2000 to 10 billion tons in 2016. During the period, Shandong province contributed most to national emissions, followed by Liaoning, Hebei, and Shanxi provinces. Most of the CO<sub>2</sub> emissions were from raw coal, which is primarily burned in the manufacturing and the thermal power sectors.

(2) Significant differences exist among provinces in terms of CO<sub>2</sub> emissions. Analyses of per capita emissions and emission intensity indicate that provinces located in the northwest and north had higher per capita CO<sub>2</sub> emissions and greater emission intensities than the central and southeast coastal regions. Developing areas have intensive resource use

and their economic structure is dominated by heavy industries with higher sectoral emission intensity. These areas contribute to most of the growth in national emissions and are the main drivers of China's carbon intensive economic structure.

(3) An analysis of the factors that affect China's CO<sub>2</sub> emissions shows that technology heterogeneity is directly connected to China's carbon growth. The dissimilar rate of adoption of energy efficient technologies among regions is a major barrier to China's CO<sub>2</sub> mitigation, and thus needs more attention from researchers and policy makers.

# 1. Challenges for China's regional low carbon development

China has recognized the need to reduce total carbon emissions and energy use, but at the same time it has prioritized economic growth to provide more employment opportunities and improve people's quality of life. Under such circumstances, it has become a major challenge to coordinate economic development with environmental protection and climate change mitigation. Established in 2007, the National Leading Committee on Climate Change (NLCCC) developed China's National Climate Change Programme, which puts forth the objectives and actions for reducing energy consumption and adapting to climate change.<sup>2</sup> Since the Copenhagen summit in 2009, China has enacted several concrete policies. The most important of these is the national commitment on climate change to reduce the intensity of carbon dioxide emissions per unit of GDP in 2020 by 40 to 45 percent compared with 2005 levels and to increase the share of non-fossil fuels in primary energy consumption to approximately 20% by 2020.<sup>3</sup> Other initiatives include restrictions on the construction of new fossil fuel power plants, increasing the use of renewable energy sources in the power sector, improving provincial energy intensity targets, as well as phasing-out of inefficient coal-burning power plants with less than 100MW capacity.<sup>4</sup> In practice, such policies are implemented in combination with the National Economic and Social Development Plan, which advocates regional "low carbon" development projects.<sup>5</sup> In the first demonstration phase five provinces and eight cities have been selected by the National Development and Reform Commission (NDRC) for pilot studies on low carbon development.<sup>6</sup>

Due to lack of scientific analysis, however, such policies cannot be effectively and efficiently designed. For instance, the recently published 12<sup>th</sup> Five-Year Plan for Social and Economic Development estimated energy intensity reduction potential for each province<sup>7</sup> directly from previous energy intensity reduction targets in the 11<sup>th</sup> Five-Year Plan (2005-2010), as well as provincial GDP levels.<sup>8</sup> But lifestyle, resource endowment, and economic development perspectives in different provinces vary, and

decision-makers will need to weigh these disparities as they develop policy and program initiatives.

The Chinese economy can be characterized as heterogeneous. While more developed eastern coastal regions have significantly improved their economy in terms of per capita income, some of the less developed western regions are still struggling to meet basic life demands.<sup>9</sup> Moreover, the income and service availability gap between urban and rural areas remains large. While most urban areas have updated their infrastructure and improved the quality of life for urban citizens, many rural areas still lack basic infrastructure (such as sanitation facilities) and face poverty reduction challenges.<sup>10</sup> Given these realities, the Chinese government should make additional strides towards recognizing that policies should consider regional disparities and their impact on the actual drivers of regional and provincial emissions.

China has experienced rapid economic development since its implementation of open and reform policies in 1978. The country is transiting from a highly centralized planning economy to a market economy.<sup>11</sup> The Chinese central government has focused on enhancing economic collaboration among different regions, while allowing regional governments to prepare their own development policies by considering their own characteristics. Based upon their natural resource endowment, industrial sector, and research and development (R&D) capacities, different provinces have specialized in different economic activities.<sup>12</sup> For instance, several provinces support the development of heavy industries due to their endowment of natural resources.<sup>13</sup> But without a comprehensive consideration of environmental and resource efficiency, these provinces are now facing severe resource depletion and environmental challenges, including the lack of treatment of coal tailings, challenges related to water/air pollution, and poor disposal of industrial solid wastes. These provinces do not have the human resources needed to upgrade their technologies and equipment and as a result must continue to rely on fossil fuels and inefficient technologies to power their economy. Such provinces include Heilongjiang, Shanxi, Xinjiang, Inner Mongolia, and Qinghai.<sup>14</sup> In contrast, provinces in coastal areas usually do not have significant natural resources, but have more developed human resources, advanced infrastructure (education,

transportation network, telecommunication facilities, etc.), and better climate conditions—these provinces support high-tech industries and service sectors, resulting in greater energy and resource efficiency.

In order to meet this challenge, a bottom-up approach that investigates various drivers of energy use and related carbon emissions in different regions is critically needed. Such an approach can help analyze both spatial and sectoral details of carbon emissions to identify regional challenges to reduce carbon emissions. To better understand the status and policy conditions for carbon emission in China, this study uses a “bottom-up” inventory of carbon emissions covering 28 economic sectors. In order to quantify both regional and sectoral disparities of carbon intensity and provincial per capita emissions, a Coefficient of Variation (CV) is applied. Moreover, a logarithmic mean divisa Index (LMDI) model is employed to uncover driving forces on carbon emissions in different provinces so that rational policy implications can be presented. Moreover, several regions have been selected as case studies to evaluate the performance of low carbon initiatives and policies.

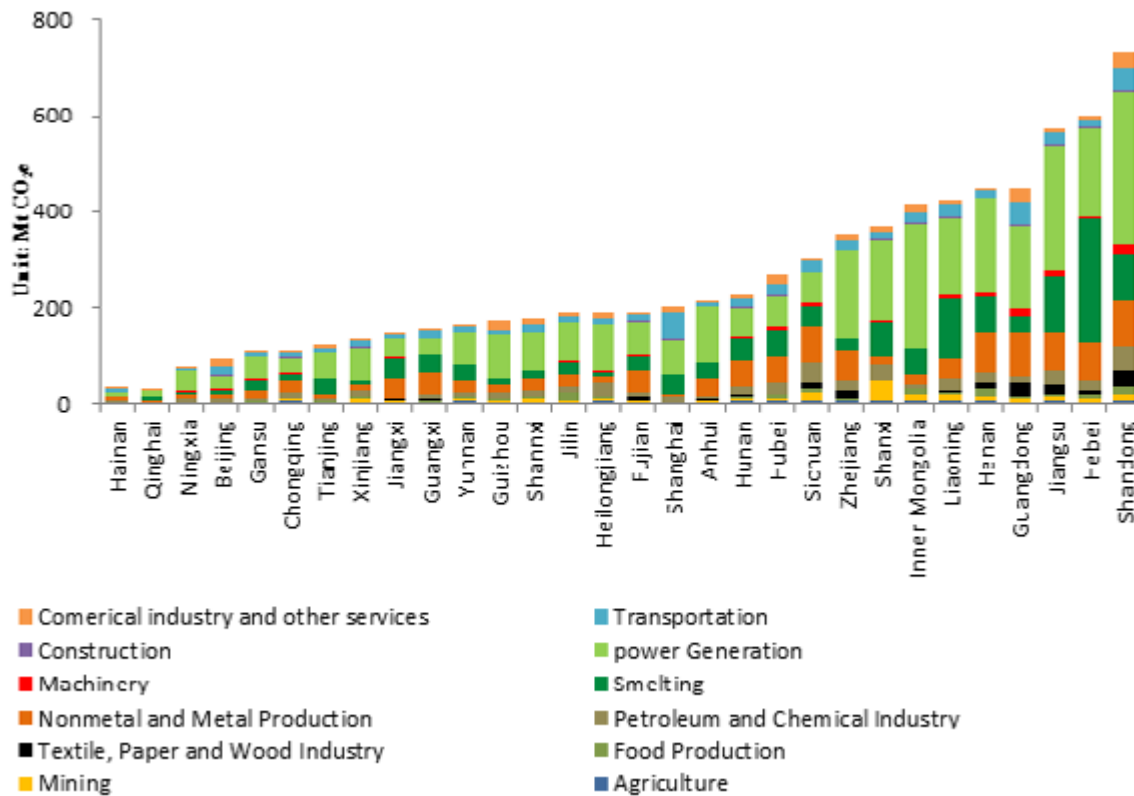
## 2. Characteristics of China’s provincial carbon emissions

The provinces that have made the largest contributions to CO<sub>2</sub> emissions from each fossil fuel type in 2012 are presented in Figure 1. Shanxi, Shandong, Inner Mongolia, and Hebei contributed the most to raw coal-related CO<sub>2</sub> emissions. The economy of these provinces is either highly reliant on coal power, manufacturing, or both. Most of the imported coal was consumed in Guangdong and Fujian, which are located on the southeast coast, where it is cheaper to import coal from abroad rather than transport it from domestic sources in the interior. Coastal Guangdong, Shandong and Liaoning also have more developed shipping industries. Most of the raw coal is consumed in thermal power plants to generate electricity.<sup>15</sup> More crude oil was consumed in these provinces, resulting in increased CO<sub>2</sub> emissions. Sichuan, Jiangsu, Xinjiang, and Beijing consumed high levels of

natural gas in 2012; Sichuan and Xinjiang are the locations of China's main natural gas fields. Jiangsu and Beijing are the most developed provinces in China and are exploring cleaner energy utilization pathways. As natural gas is a cleaner fossil fuel than raw coal and crude oil, increasing the proportion of natural gas consumption will help control CO<sub>2</sub> emissions.

The “non-metal and metal production,” “smelting and machinery,” and “power generation” sectors are three main contributors to total carbon emission. Particularly, provinces located within industrial clusters (such as Shandong and Hebei) have higher proportion of carbon emission from manufacturing related sectors, especially from the sector of “non-metal and metal production” and the “smelting” sector. Both Shanxi and Inner Mongolia are energy source rich areas (especially coal) and export a large amount of electricity to their neighboring provinces, thus they have higher proportions of carbon emission from the power generation sector.

Figure 1. **Sectoral carbon emission for different provinces**



The national average CO<sub>2</sub> emissions per capita in 2012 were 6.38 metric tons. The emissions per capita varied among provinces due to differences in development stages and development pathways. Only 13 of 30 provinces had emissions per capita above the national level.

The top three provinces were Inner Mongolia, Ningxia, and Shanxi. All three provinces are primary coal producers with many large coal mines. Mongolia and Ningxia host the China Shenhua Energy Company Limited (the nation's largest energy company), and Shanxi is the home of the China National Coal Group Corporation (the second largest energy company). These two enterprises were the only two energy enterprises in China among the 112 central enterprises (i.e., firms under government control) as of 2015.<sup>16</sup> State owned enterprises are considered in China as pillars of economic growth, with high output and added value. In addition, coal is a high-emission fossil fuel compared with crude oil and natural gas because it emits more CO<sub>2</sub> to produce the same unit of heat compared with other energy types.<sup>17</sup> Thus, these three provinces have the highest CO<sub>2</sub> emissions per capita.

The second group includes eight provinces: Xinjiang, Liaoning, Tianjin, Shaanxi, Heilongjiang, Shandong, Qinghai, and Jilin. These are either primary energy suppliers (such as Xinjiang, Shaanxi, Heilongjiang, and Qinghai) or bases for heavy industry (such as Liaoning, Tianjin, Shandong, and Jilin). The third group includes six provinces: Hebei, Shanghai, Guizhou, Jiangsu, Zhejiang, and Gansu. The CO<sub>2</sub> emissions per capita of these provinces were near the national average. The remaining 13 provinces belong to the last group. Some of these provinces are located in the central and southwest parts of China, with primary industry as their pillar economy; others are among the most developed provinces with highly developed service industries (such as Beijing and Guangdong). Jiangxi and Sichuan had the lowest CO<sub>2</sub> emissions per capita, 2.55 and 2.59 metric tons, respectively.

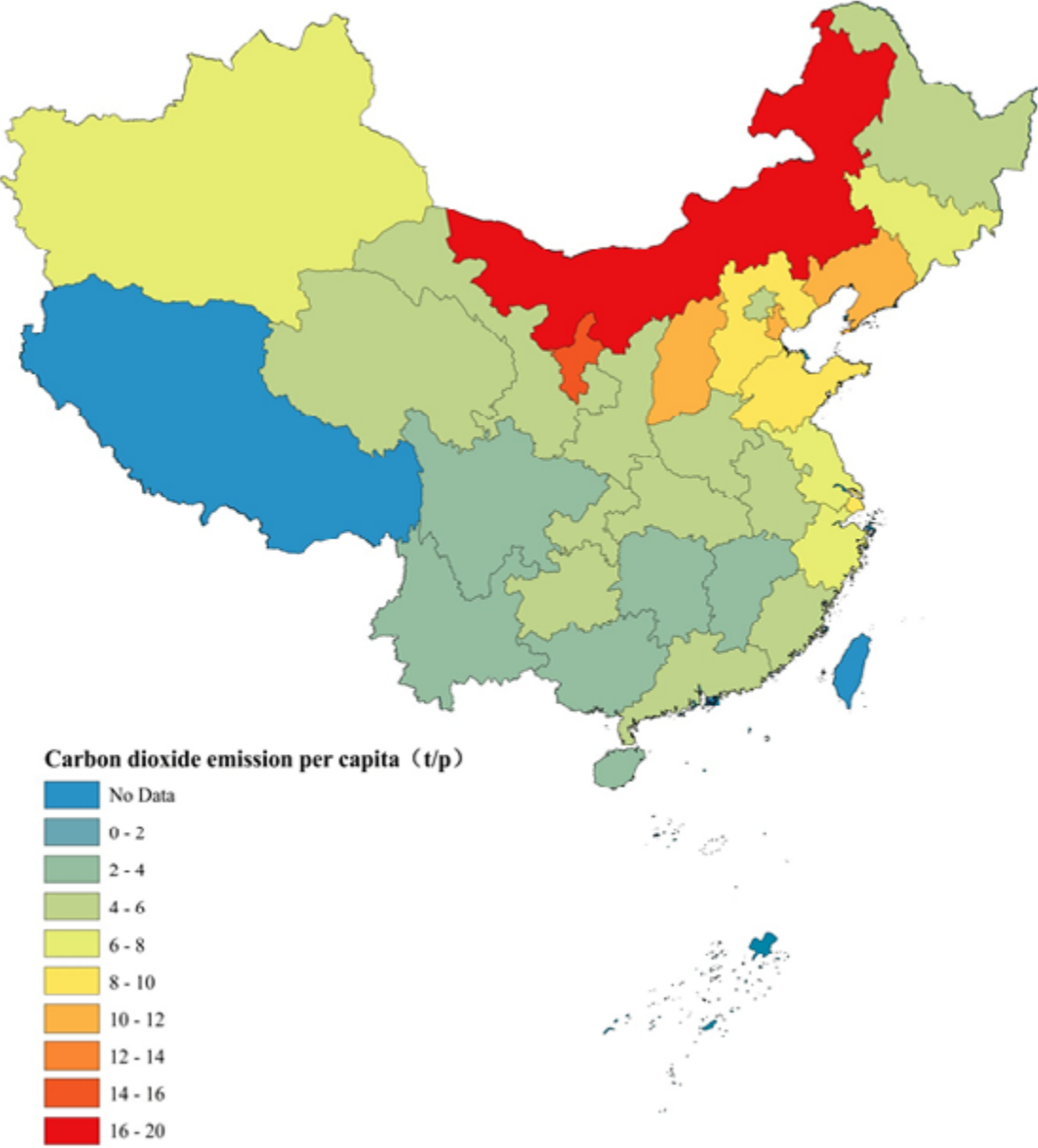
The national average CO<sub>2</sub> emission intensity in 2012 was 0.15 million tons/billion yuan. One half (15) of the provinces had an emission intensity above the national level, so the distribution of CO<sub>2</sub> emission intensity is similar to that of CO<sub>2</sub> emissions per capita. The provinces in the north

and northwest had higher emission intensities, whereas the provinces in the central and southeast areas had lower intensities. The differences in emission intensities among these provinces reflect differences in their natural resource endowments. As mentioned above, the provinces in north and northwest have more coal mines (such as Shanxi and Inner Mongolia) and oil fields (such as Xinjiang). Therefore, the industries engaged in energy production and transformation are the pillar industries of the local economy, including coal mining, coking, and petroleum processing. These industries are all high energy intensity, and huge amounts of primary fossil fuels are consumed in these provinces for refining and final consumption. CO<sub>2</sub> emissions were calculated based on energy consumption. All of the primary energy transformed into the secondary energy was included in the energy consumption numbers for the province. Hence, the CO<sub>2</sub> emission intensity of the energy-producing provinces is much higher.

By contrast, the more developed provinces have lower CO<sub>2</sub> emission intensities—these include Beijing (0.05), Shanghai (0.08), and Guangdong (0.08). These more developed provinces have greater service industries, which are less energy dependent.



Figure 2. CO<sub>2</sub> emissions per capita in 2012



The high levels of per capita CO<sub>2</sub> emissions in these underdeveloped regions can be explained by two factors: first, these regions serve as energy and resource bases which provide the electricity and industrial materials consumed in other regions. For example, more than one third of the power generated by Inner Mongolia is exported to other provinces, and the economic value of Inner Mongolia's total export to other provinces is equivalent to about 50% of the GDP produced by Inner Mongolia.<sup>18,19</sup> In comparison, the developed regions are mainly the consumers and the importers of the electricity and products supplied by less developed regions; for example, one-third of Beijing's electricity supply is generated by neighboring regions around Beijing. Second, the carbon intensity of these under-developed regions is much higher than that of the developed regions; for example, the carbon intensity of Inner Mongolia, Shanxi, and Ningxia is more than five times that of Beijing.

Figure 3. China's Provincial Carbon Emissions from 1995-1998

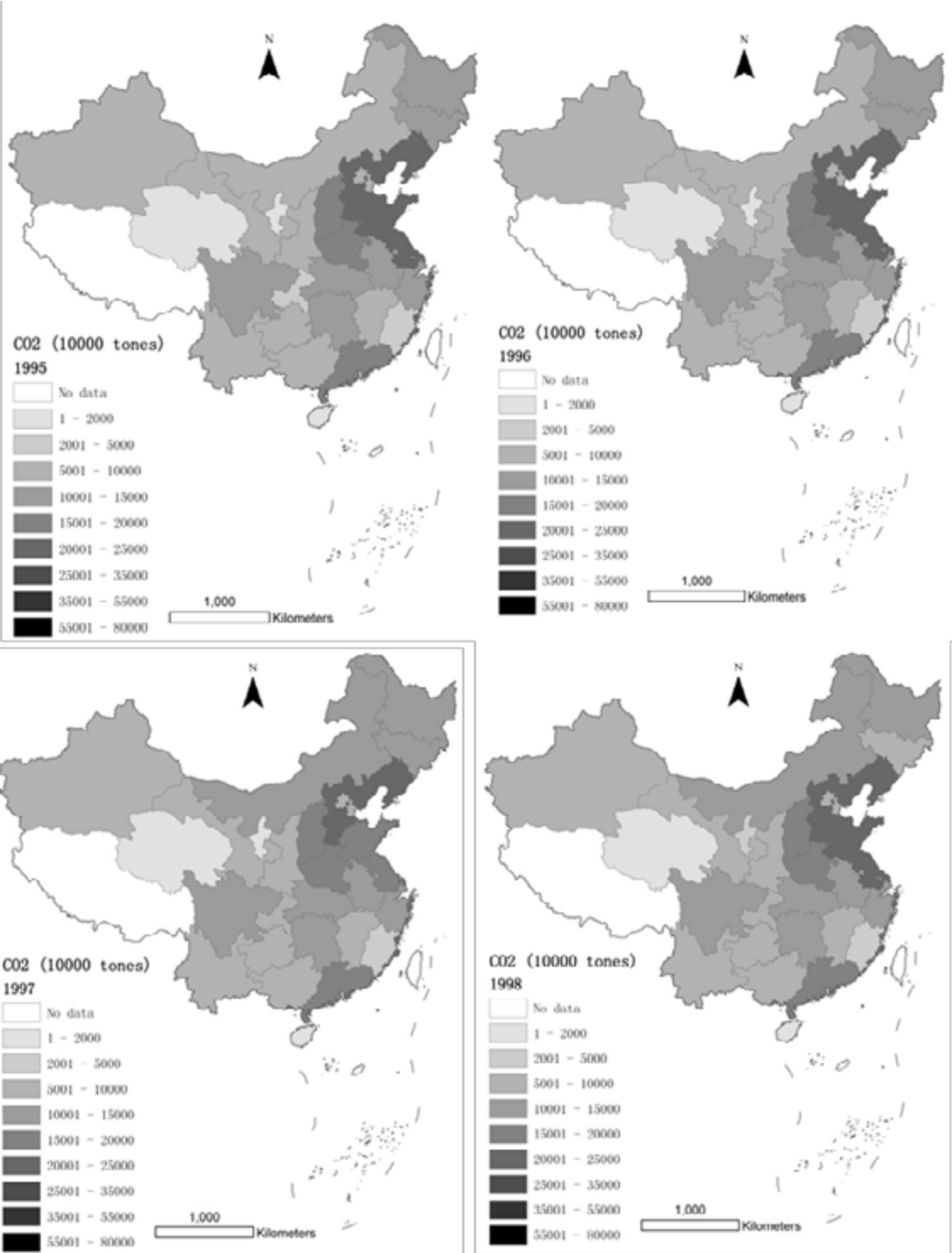


Figure 4. China's Provincial Carbon Emissions from 1999-2002

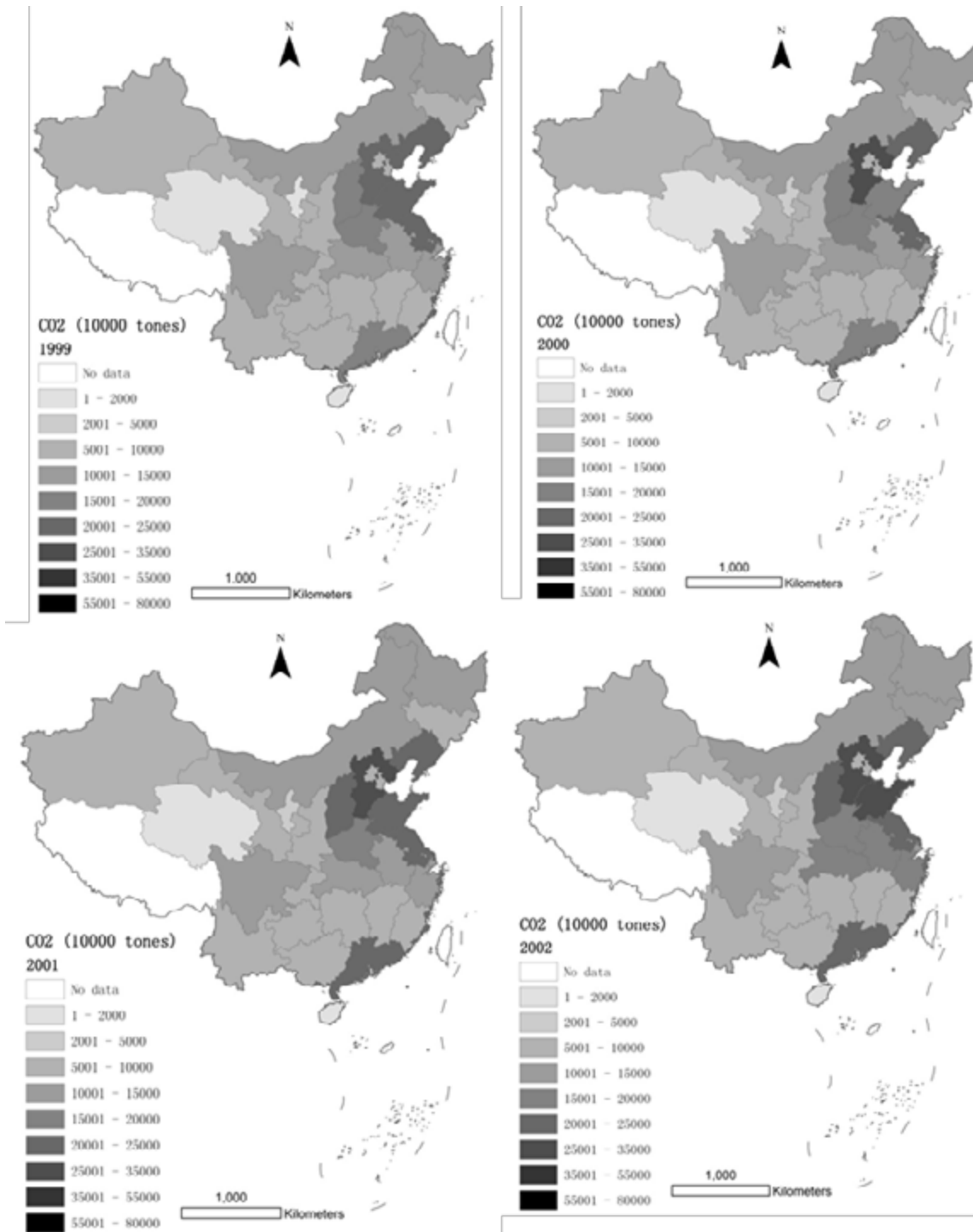


Figure 5. China's Provincial Carbon Emissions from 2003-2006

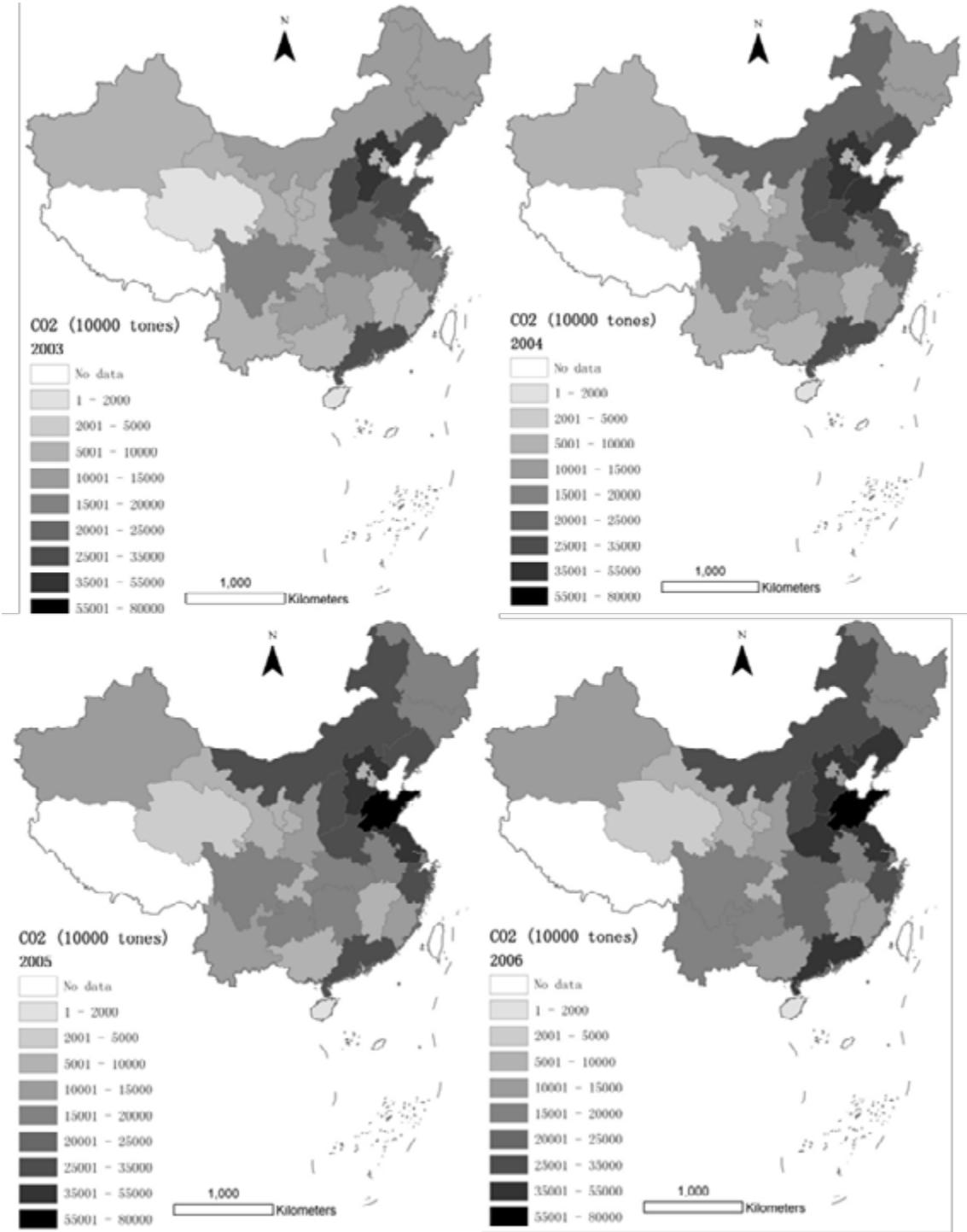
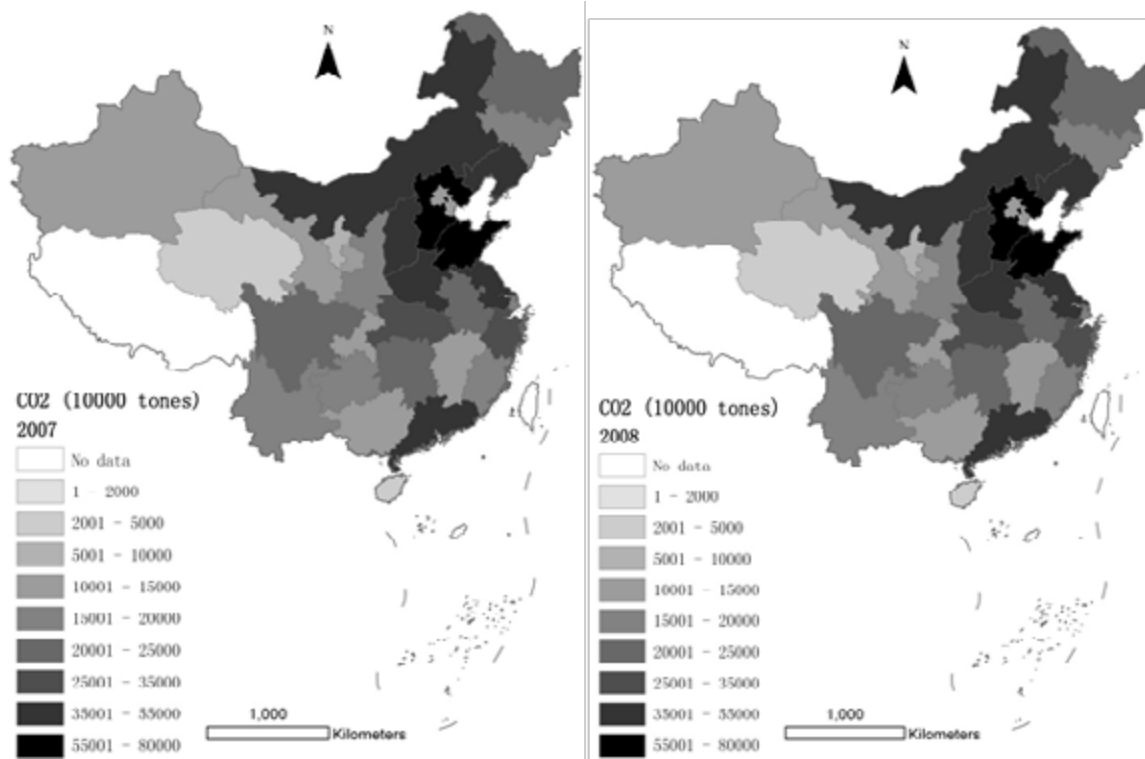


Figure 6. China's Provincial Carbon Emissions from 2007-2008



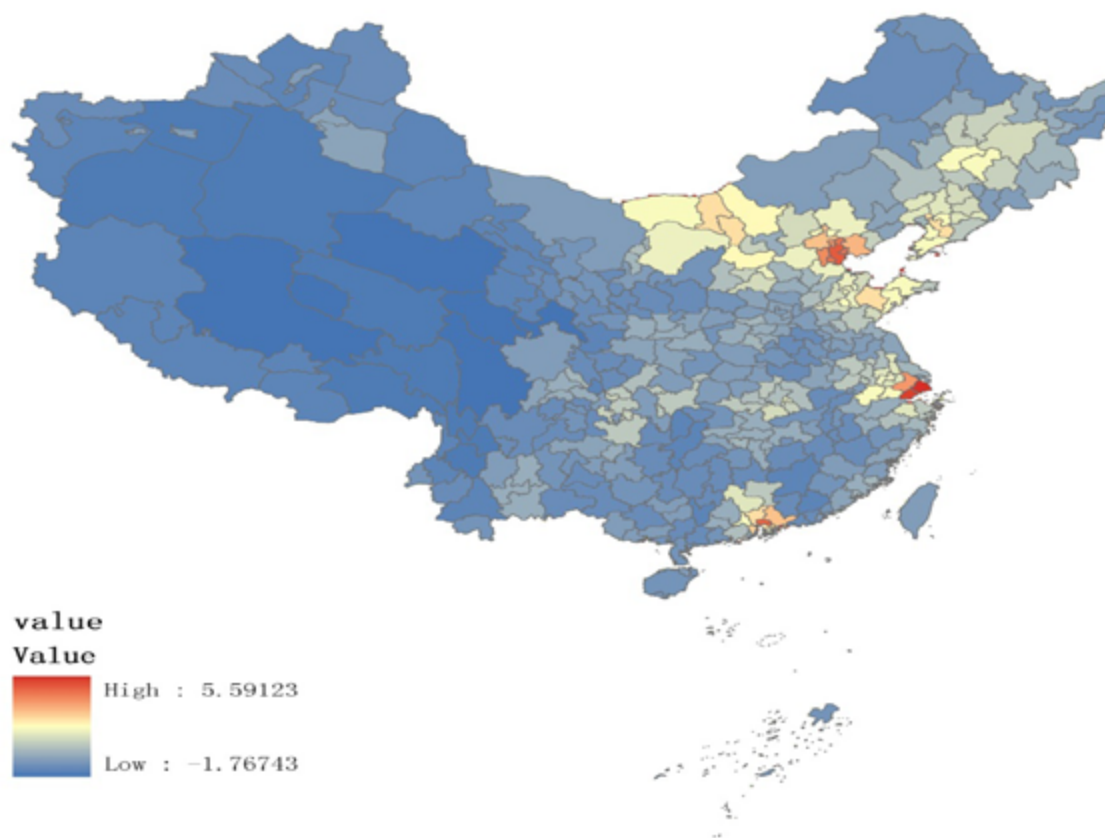
### 3. Regional variations of China's carbon emissions

I further analyzed the spatial distribution pattern of provincial carbon emissions, which is a crucial factor to evaluate environmental, social, and economic development. The spatial distribution attributes include the location, quantity, density, and auto-correlation of a spatial unit. According to Tobler's First Law of Geography, all attribute values on a geographic surface are related to each other. As the spatial autocorrelation describes the discreteness of a spatial variable, it is often used to analyze and quantify the spatial distribution, and is crucial to regional economic and environmental change studies. ArcGIS is used for analyzing the Z value (see methods for detail). Regions with high Z values are significant energy-related carbon emitters, and the surrounding areas are important contributors as well. On the contrary, regions with low Z value indicate that there is no special relation between the certain area and the surrounding areas.

Due to low resolution, the provincial carbon inventories cannot fully depict the temporal and spatial changes in carbon emissions. Therefore, the temporal and spatial extension method is applied to estimate municipal carbon emissions per unit of GDP.

Figure 7 shows the Z value of Moran's I index distribution by the temporal and spatial extension method. It is indicated that Jing-Jin-Tang, Pearl River Delta, and Yangtze River Delta are industrial centers with the highest Z values, and are also China's carbon emission hotspots.

Figure 7. **Z value of Chinese City Carbon Emissions in 2008**



## 4. Driving factors of carbon emission

With the most available data from 1997-2009, the total carbon emission and emission intensity are shown in Figure 8 (base year: 1997). During the 1997-2009 period, total carbon emissions remained relatively constant between 1997 and 2001, sharply increased from 2002-2005, and slowed down slightly after 2005. Phase changes can also be seen in historical data of carbon emission intensity. In order to find reasons for such changes, Driving factors analysis was applied for the three periods of 1997-2001, 2002-2005, and 2006-2009, respectively.

From 1997 to 2001, total CO<sub>2</sub> emissions in China remained relatively stable, with a decrease in emission intensity. There was a dramatic increase in total emissions from 2002 to 2005, and the emission intensity increased



accordingly. While total emissions have continued to increase since 2006, the emission intensity experienced a decrease after 2005. The analysis of driving factors is therefore broken down into these three time periods.

Figure 8. **Carbon Emission Intensity and Total Emission Index in China from 1997- 2009**

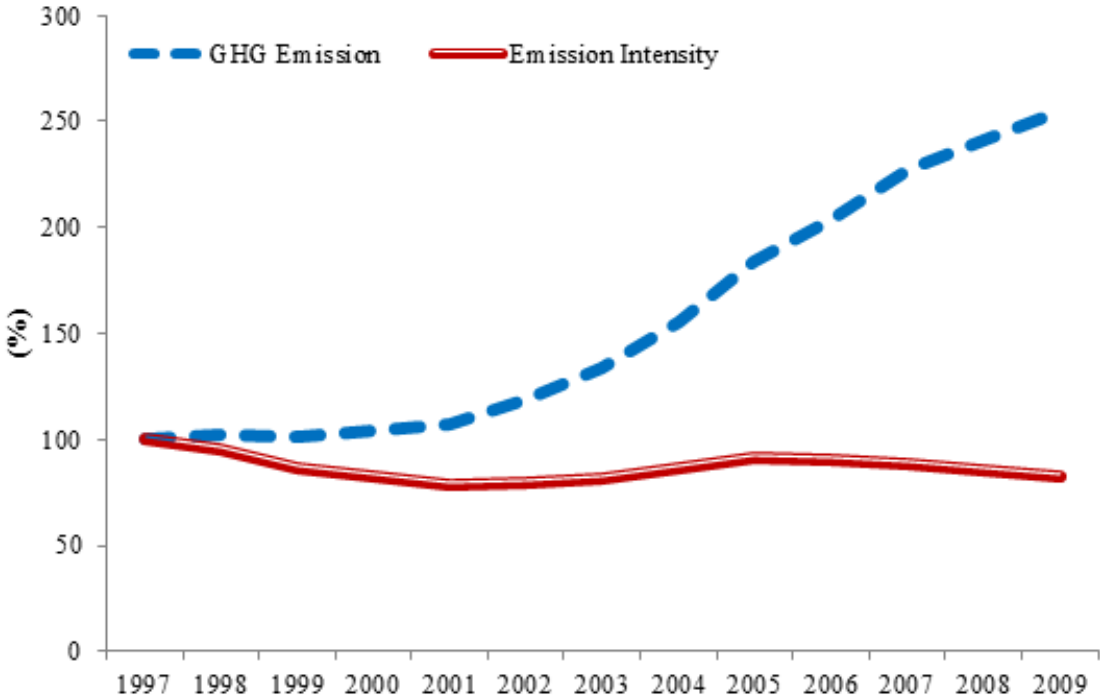


Figure 9. Driving Forces behind Carbon Emissions of 30 Provinces from 1997-2009 (unit: million tons of CO<sub>2</sub>)

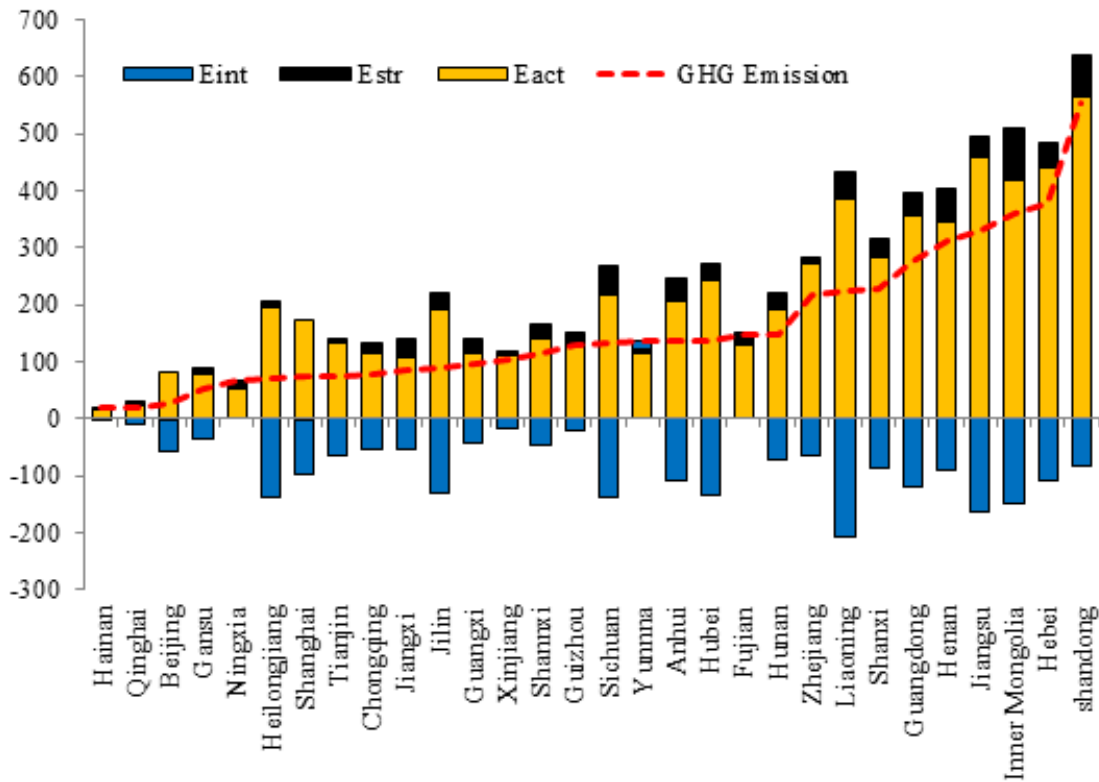


Figure 10. Driving Forces for Carbon Emission of 30 Provinces from 1997-2001 (unit: million tons of CO<sub>2</sub>)

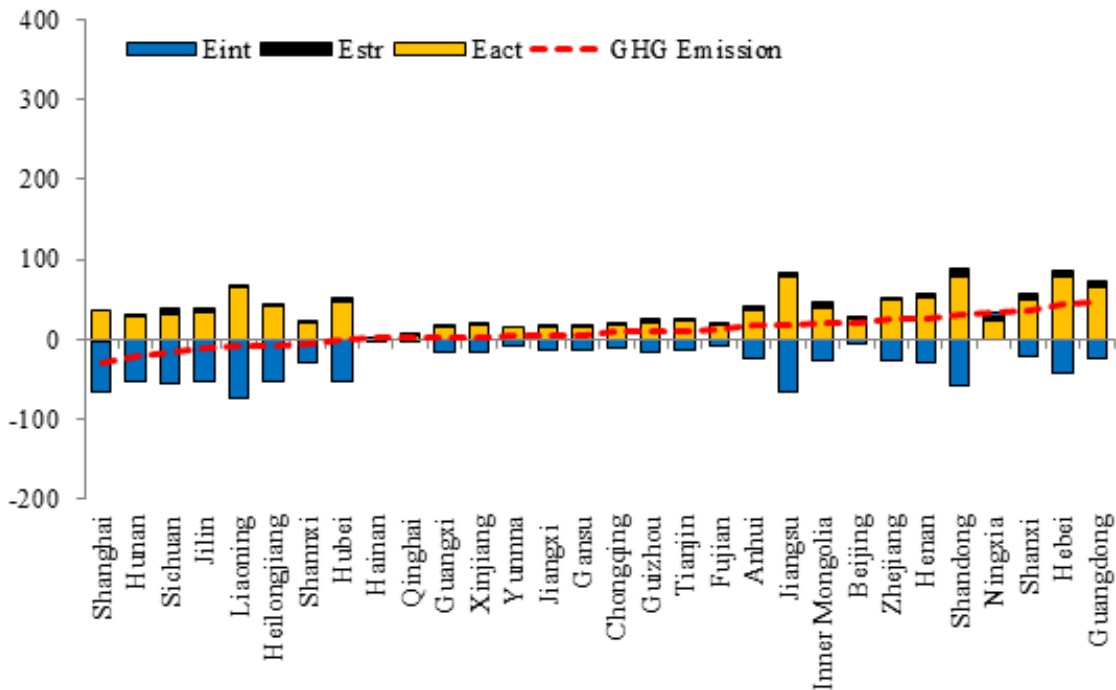


Figure 11. Driving Forces for Carbon Emission of 30 Provinces during 2001-2005 (unit: million tons of CO<sub>2</sub>)

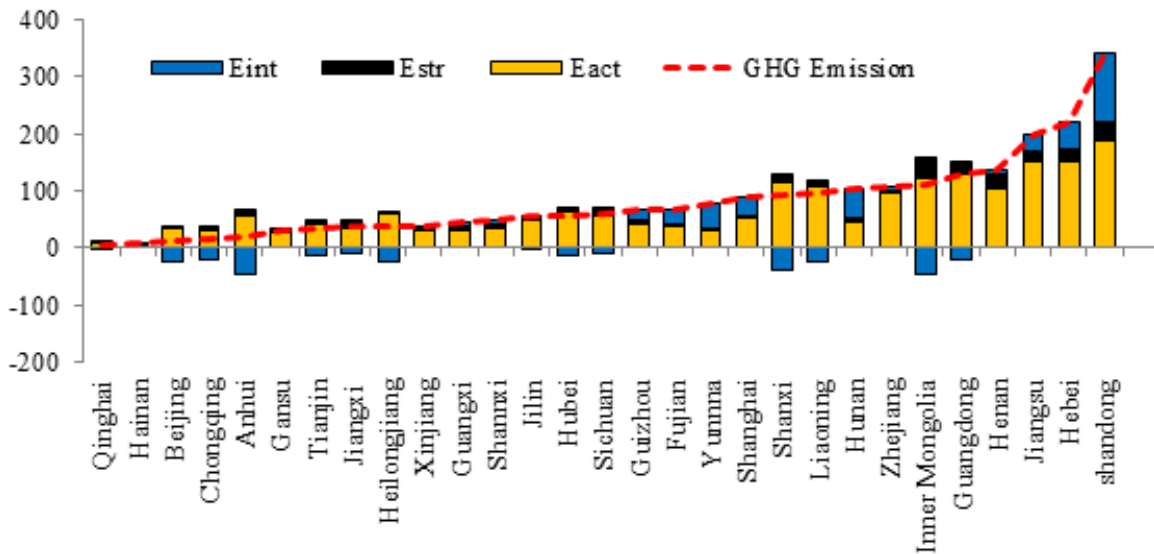
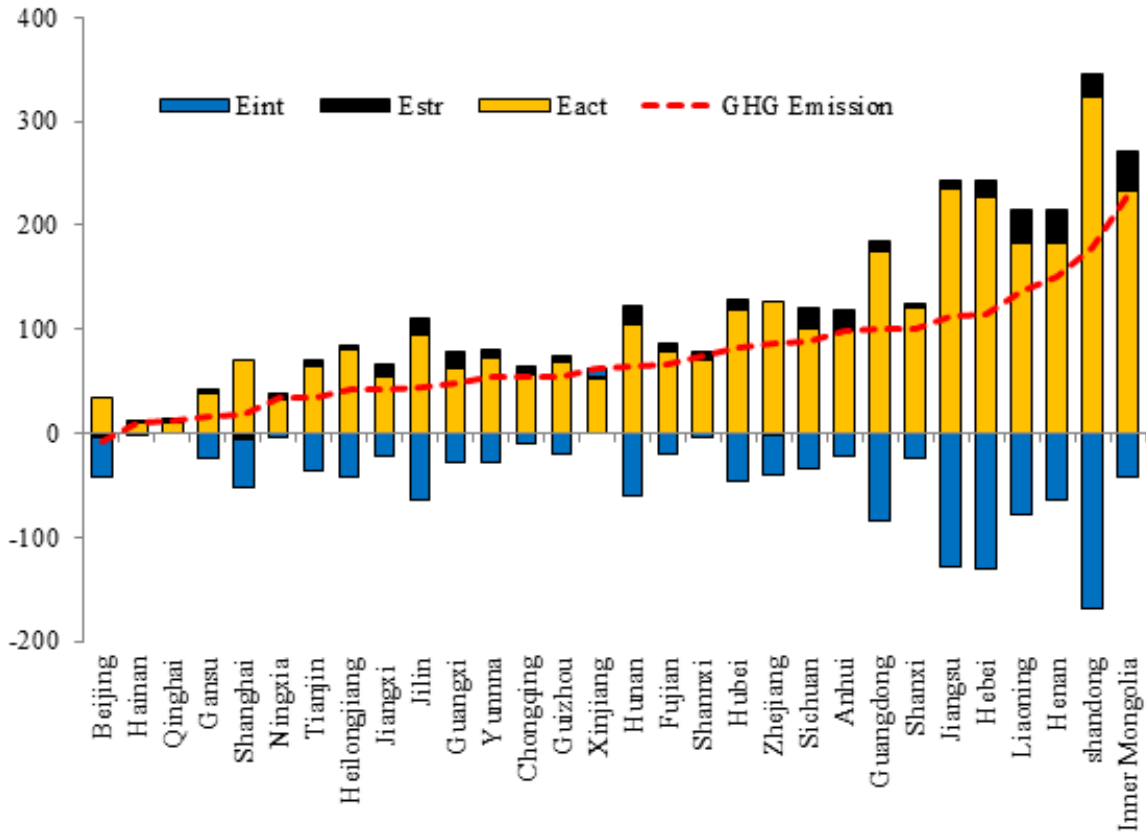


Figure 12. Driving Forces for Carbon Emission of 30 Provinces during 2005-2009 (unit: million tons of CO<sub>2</sub>)



Figures 9, 10, 11, and 12 represent the contribution from economic scale effect, economic structure effect, and technological level effect from 1997 to 2009, from 1997 to 2001, from 2002 to 2005, and from 2006 to 2009, respectively.

As shown in Figure 9, between 1997 and 2009, all provinces experienced a substantial increase in total carbon emissions. While technological advancement offsets part of the emissions increase, the economic structure effect and the proportion of heavy industry contributed positively in all provinces have been increasing.

From 1997 to 2001 (Stage I), the increase in total carbon emissions was limited, and most emissions driven by economic scale was offset by technological advancement (Figure 4.3). The total emissions of Shanghai, Hunan, and the Northeast region even declined due to economic structure adjustment. This structure effect in most provinces drove an increase in total emission.

From 2002 to 2005 (Stage II), all provinces experienced a dramatic increase in total carbon emission. The economic scale, economic structure, and emission intensity contributed significantly and positively to total carbon emission.

From 2006 to 2009 (Stage III), the provincial carbon emission levels continued to increase, represented by the increase in economic scale. While the emission intensity effect dropped significantly, the economic structure still relied on 'heavy' industry. However, with the decline in emission intensity, growth was half that in the preceding five years.

## 5. Conclusion and Policy Discussions

China's regional and sectoral carbon emission patterns and their driving forces are explored in this paper by using detailed energy consumption data at the sector level. I constructed for each province a detailed carbon emission inventory covering 28 sectors and used an index composition analysis to explore disparity. Results uncovered significant differences in sectoral emission intensity among provinces, implying a huge disparity of technology level among regions. Less developed provinces with much higher energy intensive technologies contribute to most of national emission increment and cause the whole country's economic structure to become carbon intensive. Our research indicates that the inequity of technology levels between regions is a main barrier for China's CO<sub>2</sub> mitigation efforts and deserves more attention from researchers and policy makers.

Generally, our research results illustrate the significant disparity of carbon emissions between Chinese provinces from both spatial and sectoral perspectives. The results conform to Chinese economic development history and can better explain China's carbon emission trends. Regions with higher total carbon emissions are also those with highly concentrated manufacturing and mining industries, especially Hebei, Shandong, Shanxi, and Inner Mongolia. These provinces are rapidly developing areas and in urgent need of decoupling their economic growth from environmental consequences. Several provinces, such as Inner Mongolia, Ningxia, and Shanxi, have both higher per capita carbon emission and higher emission intensity, implicating lower energy efficiency and a great potential for carbon emission reduction.

China's overall economy is largely dependent on its primary energy resources. But such resources are mainly located in less developed regions. Due to a lack of advanced technologies, equipment, and management experiences, energy efficiency in these regions is much lower than those in more developed provinces. Also, with the relocation of energy intensive industries from coastal areas to inland areas and increasing dependence on

natural resources from these resource-rich areas, energy intensity in such regions has dramatically increased.

Furthermore, unprecedented urbanization brought another challenge. Between 1997 and 2006 in China, a total of 12,869 km<sup>2</sup> of land was converted into built-up areas, stimulating a great demand for basic infrastructure, including water, electricity, Internet, wastewater treatment, gas, roads, and heating. Finally, increasing quality of life in urban areas further pushed the total carbon emission increments due to the soaring demand on larger living space, more vehicles, and greater use of home electronic appliances. For instance, China has become the world leader for both vehicle manufacturing and sales since 2009, leading to a huge amount of steel and gasoline consumption and a remarkable investment in transportation infrastructure.

Combining the above information with my research outcomes, significant policy implications can be identified and appropriate policy recommendations provided to decision-makers. First of all, my research results confirm China's imbalanced development and suggest that current energy intensity reduction targets for different provinces should be revised. For example, both the Beijing municipality (politically equal to a province) and Liaoning province were ranked as "second level" regions, and were assigned the second highest emission reduction targets (17% energy intensity reduction target). Over the previous decade many energy intensive industries have been relocated outside Beijing's jurisdiction. On the other hand, Liaoning province, with a large industrial base, is not able to export their industrial base and shift its environmental burden. This unequal playing field and perceived lack of fairness has caused provincial officials to take these emission reduction goals less seriously. Consequently, conducting a thoughtful scientific analysis considering variations in resource endowment and region specific development is necessary to establish provincial emission targets so that the impacts on regional and industrial sectors can be seriously considered.

Second, the LMDI analysis indicated that the economic activity effect is the dominating factor driving the increase in total carbon emissions. Since the total economic scale is still increasing and the Chinese energy structure

is still fossil fuel based, it is not easy to reduce its impact in a short time period. However, efforts should still be made to optimize the energy structure and improve energy efficiency. For example, in order to increase the total consumption of renewable and clean energy, a large sum of money has been invested to support the application of renewable/clean energy, such as wind power, solar energy, geothermal energy, and natural gas. To date, China has become the largest wind power and solar power generation country in the world. Compared with the year 2008, the percentage of renewable/clean energy over total energy consumption in 2009 increased from 8.4% to 9.9%. In order to improve efficiency levels, energy inefficient and obsolete production facilities should be phased out and replaced with energy efficient plants. An active education and outreach campaign should be initiated (including TV promotions, newsletters, and regional symposia and workshops) to increase the overall public awareness of energy saving and emission reduction potential. Such initiatives can provide forums through which energy efficiency experiences from different parts of the world and from different institutions could be objectively reviewed and lessons drawn. These activities can also create opportunities for stakeholders to strengthen their mutual understanding, trust, and respect, which will create a solid foundation for further collaboration.

Third, the LMDI analysis uncovered that changes in China's industrial structure had a positive effect on total carbon increase during the investigated periods. In order to meet the increasing demand on natural resources and domestic consumption, many mining and manufacturing companies have been established since 2002. For instance, to support rapid domestic auto industry development, the national government has encouraged consumers to purchase motor vehicles. These environmentally counterproductive social and economic policies have resulted in China becoming the world's No. 1 vehicle market, resulting in record emissions of hydrocarbons, nitrogen oxides, and particulate matter. Other sectors, such as construction and power generation, have also seen unprecedented growth due to increasing energy demand from industrial development and China's rapid urbanization. Therefore, the government's focus should move to adjusting the country's industrial structure. Since the service sector can dramatically reduce the dependence on resource/energy-intensive sectors, substantial efforts should be made to promote the rapid transition to a

more service oriented economy. Such a policy can facilitate scientific and technological innovation and fuel the next stage of green growth. Another approach is to support the circular economy, namely, the realization of a closed loop of material flows in the whole economic system. In order to achieve better performance, such a policy should be implemented at three levels, including: (a) eco-design and cleaner production at the corporate level; (b) industrial symbiosis and eco-industrial park at an industrial sector level; and (c) 3R (reduction, reuse, and recycling) networks at a regional level.

Fourth, success in achieving national energy saving and emission reduction goals requires effective economic and regulatory policies. Thus, economic, market-based, policy instruments should be adopted to help alter industrial and consumer behaviors. One such instrument is the use of tradable permits, granting a specific carbon emission allowance to an organization with freedom to sell excess allowances to other organizations. It is a flexible regulatory policy instrument that can be used to compensate for higher costs of pollution prevention projects in one region or in one industrial sector, allowing energy intensive companies to seek a variety of methods for reducing their carbon emissions, including purchasing allowances (“cap-and-trade” is an example policy). Another economic policy instrument is price reform. Currently natural resources prices (rents) within China are low and do not reflect their true total social cost. Given this underpricing, organizations are inclined to use natural resources inefficiently, e.g. through overuse or inappropriate use. Increasing natural resources prices (especially primary energy source, such as coal and oil) by incorporating consideration of their availability, supply, and final treatment will provide economic incentive for rational industrial natural resource consumption.

Finally, a national coordination mechanism should be established to avoid emission transfers among different provinces (e.g. the shifting of Beijing’s emissions to other regions). A perverse outcome of poor national coordination of emissions is an intra-national “pollution haven” search. Rich provinces tend to relocate polluting or energy intensive industries by taking advantage of poorer provinces’ economic development needs. Thus, a national coordination mechanism will prevent poorer and more



vulnerable regions from suffering greater environmental burdens from transference of industrial emissions.

## Methodology

This study uses production-based carbon emission inventory for carbon emissions accounting. Although much attention has recently been paid to a consumption-based emission accounting scheme,<sup>20,21</sup> it was decided to only focus on production-based emissions accounting in order to keep in line with China's national carbon inventory reported for the United Nations Framework Convention on Climate Change (UNFCCC).

Under this framework, carbon emissions (tons CO<sub>2</sub>eq) from 30 provinces (including Beijing, Tianjin, Shanghai, and Chongqing, which are four municipal cities politically equal to one province) were calculated based on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.<sup>22</sup> A detailed inventory covering carbon emission from 28 sectors was constructed in order to analyze the distribution and disparity of carbon emission among different regions and sectors. The full accounting approach followed the one proposed by Peters et al.<sup>23</sup>

Energy consumption in physical units of 28 economic sectors was calculated by using sectoral information listed in Table 2. 15 types of fuels were considered for driving energy consumption in each sector. Table 3 lists carbon emission factors (EF) for different fuels. Total carbon emissions were derived from direct CO<sub>2</sub>, N<sub>2</sub>O, and CH<sub>4</sub> emissions and can be calculated through the use of equation 1.

$$E_{GHG,(k,i)} = \sum_i \sum_j C_{ij} EF_j O_j M \quad (1)$$

Where  $k$  represents region;  $C_{ij}$  is the energy consumption (TJ) of fuel type  $j$  from  $i$  sector;  $EF_j$  is the carbon emission factor of type  $j$  fuel (t C/TJ);  $O_j$

is the oxidation rate of fuel type  $j$ ; and  $M$  is the molecular weight ratio of carbon dioxide to carbon (44/12).

Further, the 28 economic sectors were categorized into five main economic sectors (Agriculture, Manufacturing, Construction, Commercial Industry, and Transportation) to present the time-series carbon inventory.

It should be noted that boundary definition will fundamentally affect the carbon emission inventory, due to cross-boundary carbon emissions embodied in exchange of goods, services, commuter travel, and aviation.<sup>24</sup> In this study regional emission inventory was kept in line with the definition of scope 1 emission (production-based emission), which was based upon territorial emissions (or say, direct use of primary energy within a territorial boundary).<sup>25-27</sup> The reason for doing so is because carbon intensity targets set by the Chinese government were based upon the territorial principle.

## Coefficient of Variation Analysis

The analysis of coefficient of variation (CV) was used to investigate the differences in per capita carbon emission from each province, as well as the emission intensity of each sector among different provinces. The value of CV can be calculated through the use of equation 2:

$$CV = \frac{\sqrt{\sum_{i=1}^n \frac{\sum (x_i - \bar{x})^2}{n}}}{\bar{x}} \quad (2)$$

Where  $x_i$  represents the per capita emission of province  $i$  (or emission intensity of sector  $i$ );  $n$  represents the total number of provinces or sectors, and  $\bar{x}$  is the mean value of all  $x_i$ .

Provincial GDP value and population are available from *Chinese Statistics Yearbook*.<sup>28</sup> Carbon emission intensity was calculated by using the sector's carbon emission divided by its total output. Total output was obtained

from the Chinese input-output table published in *Chinese Statistics Yearbook*.

## Index Decomposition Analysis

In this study, driving forces for the historical change of carbon emissions were decomposed into three factors: overall industrial activity (Activity Effect), activity mix (Structure Effect) and sectoral carbon emission intensity (Intensity Effect). Activity effect describes the contribution of GDP to carbon emission increase, namely, total economic scale. Structure effect is an indicator for evaluating the contribution of industrial structure change on carbon emission increase. Intensity effect refers to the effect of carbon intensity (carbon emissions per unit GDP) on carbon emission increase and is used to evaluate the contribution of technology improvement on carbon emission reduction since the application of more advanced technologies can improve energy efficiency and lower carbon intensity. Comprehensive description of activity effect, intensity effect, and structure effect and the associated calculation have been introduced by Ang.<sup>29</sup> Equation 3 illustrates how to conduct index decomposition analysis.

$$E = \sum_i E_i = \sum_i Q \frac{Q_i}{Q} \frac{E_i}{Q_i} = \sum_i Q S_i I_i \quad (3)$$

Where  $E$  represents emissions from aggregate industrial sectors;  $Q$  represents the total GDP from all the industrial sectors; and  $S_i$  and  $I_i$  represent the GDP share and carbon intensity of sector  $i$ , respectively. Thus, based upon the LMDI approach, driving factors on emissions from baseline year to final year can be expressed as:

$$\Delta E = E^t - E^0 = \Delta E_{act} + \Delta E_{str} + \Delta E_{int} \quad (4)$$

Where  $\Delta E$  is the aggregate change of carbon emission from baseline year ( $E^0$ ) to final year ( $E^t$ ),  $\Delta E_{act}$ ,  $\Delta E_{str}$ , and  $\Delta E_{int}$  represent the changes of activity

effect, structure effect, and intensity effect between baseline year and final year, respectively. Where  $\Delta E_{act}$ ,  $\Delta E_{str}$ , and  $\Delta E_{int}$  can be expressed by:

$$\Delta E_{act} = \sum_i w_i \ln \left( \frac{Q^t}{Q^0} \right) \quad (5)$$

$$\Delta E_{str} = \sum_i w_i \ln \left( \frac{S_i^t}{S_i^0} \right) \quad (6)$$

$$\Delta E_{int} = \sum_i w_i \ln \left( \frac{S_i^t}{S_i^0} \right) \quad (7)$$

$$w_i = \frac{E_i^t - E_i^0}{\ln E_i^t - \ln E_i^0} \quad (8)$$

Where  $w_i$  represents logarithmic mean divisa weight for sector  $i$ .

## Spatial autocorrelation analysis

Spatial autocorrelation measures the degree of dependency among observation units in a geographic space (Goodchild, 1986). The spatial autocorrelation statistics transform the observation values to binary symmetric spatial weights matrix  $W$  to reflect the geographic relationships between  $n$  locations:

$$W = \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1n} \\ w_{21} & w_{22} & \cdots & w_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ w_{n1} & w_{n2} & \cdots & w_{nn} \end{bmatrix} \quad (9)$$

The spatial weights matrix  $W_{ij}$  represents the intensity of geographic relationship between regions  $i$  and  $j$ . Since the spatial attribute (energy-related carbon emission) in this study is a single value, and the space of each province is different with irregular shape, the adjacency rule is adopted (Lu and Xu, 2007).

$$w_{ij} = \begin{cases} 1 & \text{When } i \text{ and } j \text{ are spatially linked} \\ 0 & \text{Others} \end{cases} \quad (10)$$

The spatial correlation index represents the degree of geographical relationship by a dimensionless value. Moran's  $I$  index is used in this study (Getis and Ord, 2010; Goodchild, 1986; Lu and Xu, 2007):

$$I = \frac{n \sum_{i=1}^n \sum_{j=1}^n w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^n \sum_{j=1}^n w_{ij} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (11)$$

$I$ : Moran's  $I$  index

$x_i$ : Attribute value of region  $i$ , represented by the energy-related carbon emission

The value of Moran's  $I$  index ranges  $[-1,1]$ , with negative numbers for discreteness, positive numbers for aggregate, and zero for randomness. Moran's  $I$  index can be further standardized as statistical value  $Z$  to test the spatial autocorrelation between  $n$  regions.

$$Z = \frac{I - E(I)}{\sqrt{VAR(I)}} \quad (12)$$

$Z$ : standardized statistical value

$E(I)$ : expectation of Moran's  $I$  index

VAR(I): variance

Positive and notable Z value indicates the positive spatial autocorrelation, represented by the aggregate of similar observational values (high or low). Negative and notable Z value indicates the negative spatial autocorrelation, represented by the discreteness of similar observational values. Zero indicates random distribution of the observations.

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