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ORIGINAL ARTICLE

Impacts of booming economic growth and urbanization on carbon dioxide emissions in Chinese megalopolises over 1985–2010: an index decomposition analysis

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Abstract Given the booming economic growth and urbanization in China, cities have become crucial to sustaining this development and curbing national emissions. Understanding the key drivers underlying the rapid emissions growth is critical to providing local solutions for national climate targets. By using index decomposition analysis, we explore the factors contributing to the carbon dioxide (CO_2) emissions in Chinese megalopolises from 1985 to 2010. An additional decomposition analysis of the industry sector is performed because of its dominant contribution to the total emissions. The booming economy and expanding urban areas are the major drivers to the increasing CO_2 emissions in Chinese megalopolises over the examined period. The significant improvement in energy intensity is the primary factor for reducing CO_2 emissions, the declining trend of which, however, has been suspended or reversed since 2000. The decoupling effect of the adjustments in the economic structure only occurred in three megalopolises, namely, the Yangtze River Delta (YRD), the Beijing-Tianjin-Heibei Megalopolis (BTJ), and the Pearl River Delta (PRD). In comparison, the impacts of urban density and carbon intensity are relatively marginal. The further disaggregated decomposition analysis in the industry sector shows that energy intensity improvements were widely achieved in 36 sub-industries in the PRD. The results also indicate the concentrations of energy-intensive industries in the PRD, posing a major challenge to local governments for a low-carbon economy. As economic growth and urbanization continue, reductions in energy intensity and clean energy therefore warrant much more policy attentions due to their crucial roles in reducing carbon emissions and satisfying the energy demand.

Keywords Carbon dioxide emissions · Driver · Index decomposition analysis · Chinese megalopolis

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Introduction

Urbanization (including the aggregation of population in urban areas and the expansion of urban areas) has been recognized as one of the global environmental phenomena of the twenty-first century (Seto and

Shepherd 2009). It alters local environments through a series of physical phenomena that result in local environmental stresses (Seto et al. 2014). China is currently in a capital-intensive stage of industrialization and urbanization, producing a quarter of global fuel-related carbon dioxide (CO_2) emissions in 2010 (Boden and Blasing 2011). On the one hand, with more than half of the population now living in cities, urban dwellers in China emit impressively higher per capita CO_2 emissions than the national average (IEA 2011). On the other hand, urban areas contain the potential of using the aggregated knowledge, creativity, and technology to reduce the emissions (Kennedy et al. 2009). In its latest Five-Year Plan (FYP), the Chinese government calls for the energy and carbon intensity to decline an additional 16 and 17%, respectively, from the 2010 level by the end of 2015 (the State Council 2011). The local governments, therefore, are addressing national pressures, firmly guided by reduction targets and policies (Gertz 2009).

Given that rapid economic growth and urbanization lead to a surge in energy consumption, many scholars have conducted extensive studies on the driving effects of economic growth and urbanization on CO_2 emissions at a national or provincial scale, without consideration for the differences hidden behind the spatial scales (Wang et al. 2014c; Xu and Lin 2015). Due to China's vast territory, case studies on national and provincial levels are not sufficient enough for policy makers aiming to realize carbon reduction targets. On the one hand, Chinese cities produce 75% of the national gross domestic product (GDP) and account for 84% of national commercial energy consumption (Liu et al. 2012b). Therefore, these cities make significant contributions to the increasing level of anthropogenic CO_2 emissions, and they also play a crucial role in achieving the carbon reduction target as well. On the other hand, cities are sensitive to carbon reduction actions, due to the concentrations of heavily energy-reliant activities within cities (Satterthwaite 2008). Thus, local governments are confronting severe conflicts between the energy demand caused by the booming economic growth and urbanization and the energy reduction targets established by the upper levels of governments. Linyi, an industrial city in Shandong Province, shut down 57 energy-intensive enterprises to ensure that it met the reduction target set by the National Ministry of Environmental Protection, causing an economic loss of 350 billion Yuan in the first quarter of 2015 (Xinhua Net 2015). Thus, the following questions are critical for policy makers aiming to have low-carbon growth: what are the trajectories of energy consumption and CO_2 emissions at the city level in China? How do economic growth and urbanization affect CO_2 emissions? Unfortunately, the answers to these questions are scarce due to several methodological challenges in the estimation of CO_2 emissions at the city level in China, such as the determination of boundaries and data availability (Seto et al. 2014).

Hence, this study fills this gap by employing an energy data set at a city level in China developed by our previous works (Meng et al. 2014). Ten megalopolises in China are chosen due to their prominent contributions in the field of economic growth and urbanization as well as in total energy consumption. The main objective of this paper is to quantify the driving effects of economic growth and urbanization on CO_2 emissions in the ten megalopolises through a decomposition analysis. In contrast to previous studies (Kang et al. 2014; Ma 2015), we explore the differences in CO_2 emissions and their drivers between the ten megalopolises in China. Four sectors, including industry, construction, transportation, and service sectors, are analyzed separately with a particular focus on the industry sector. Firstly, we present the uncertainty of the data set used in this study. We then calculate the patterns of energy-related CO_2 emissions by sectors occurring in the ten megalopolises by sector. Finally, we estimate the contributions of the underlying drivers in Chinese megalopolises, using the method of index decomposition analysis method.

The results indicate that economic growth contributes the largest driving force of CO_2 emissions in urban China, followed by expansion of urban areas. Improvement in energy intensities is the major approach to satisfying carbon emission reduction targets. However, the decoupling effects of energy intensities have slowed down and even reversed in some megalopolises since 2000. From a sectoral perspective, the economic structures in the three most developed megalopolises, i.e., the Yangtze River Delta (YRD), the Beijing-Tianjin-Heibei Megalopolis (BTJ), and the Pearl River Delta (PRD), shift from industry dominant to industry-service dominant, making the economy greener. However, the urbanization effect induces construction activities and the growth of energy-intensive industries, making a positive contribution to the increasing CO_2 emissions. The decomposition results may be beneficial for local governments with regard to urban management and emissions reduction policies in Chinese cities.

The rest of this paper is organized as follows. The section "Literature review" provides a literature review on the driving factors of the CO_2 emissions, with a consideration of spatial scale. The section "Methodology and data" specifies the model and the data set used in this study. The section "Results" presents the results of this study, and the discussions occurs in "Discussions" section. The section "Conclusion" establishes out the main conclusions and a series of implications for local governments.

Literature review

The Kaya identity is one of the topical decomposed identities for decomposing total emissions into four factors: population, per capita GDP, the energy intensity of GDP, and the carbon intensity of energy (Kaya 1989). Motivated by the Kaya identity, the existing literature has been extensively concerned with the relationship between economic growth, energy consumption and CO_2 emissions at multi-spatial scales. Using the Kaya identity, Raupach et al. (2007) concluded that the explosive emission growth in developing countries is driven by a resource-intensive economy and urbanization, partly offset by improvements in the energy intensity of GDP and structural effects. It is projected that the non-OECD (Organization for Economic Co-operation and Development) countries would account for 81% of energy consumption growth by 2030 and that urbanization would account for 25% of the projected growth (O'Neill et al. 2010). Zhang and Lin (2012) found a positive relationship between urbanization and CO_2 emissions at the national and regional levels in China. They noted that there are significant regional differences in the impacts of urbanization on CO_2 emissions. Feng et al. (2012) found that the energy intensity and carbon intensity of GDP are crucial in meeting the energy demand and in curbing CO_2 emissions. They also noted that urbanization and the associated income and lifestyle changes were important driving forces for the growth in CO_2 emissions in China. This conclusion is also supported by Ma (2015), who found that in the short term, urbanization significantly increases energy intensities in China. Without exception, all the abovementioned studies highlight that there are significant regional differences in the physical geography, regional economy, demographics, and industry structure across China, leading to large regional discrepancies in CO_2 emissions. Thus, the current studies focusing on the national and provincial level are not sufficient enough to provide specific policy implications for city governments.

There are few studies conducted at the city level. It is estimated that in cities in developing countries, such as Beijing, Shanghai, Guangzhou, and Bangkok, over 60% of the total CO_2 emissions are contributed by the industry sector (Croci et al. 2011; Wang et al. 2012), whereas in developed counties, emissions from buildings, including both household and commercial buildings, are the largest contributor (Croci et al. 2011). However, on a per capita basis, urban dwellers in developing countries, however, emit much more CO_2 than the national average, due to higher income, change in lifestyle, and easy access to electrical appliances (Feng et al. 2012). In Tianjin, one of the typical industrial cities in China, economic growth was the most important factor increasing the CO_2 emissions, whereas energy efficiency improvements were primarily responsible for the decrease in emissions (Kang et al. 2014). In Suzhou, the economy and the population were the major drivers of greenhouse gas (GHG) emissions, and a decline in carbon intensity was the major contributor offsetting these emissions. Both the case studies in the two Chinese cities reach similar conclusions. Urbanization drives the overall energy intensities up among China's provinces (Ma 2015). However, little attention has been paid to the impacts of urban expansion on CO_2 emissions at the city level. This study fills this gap by quantifying the contributions of the driving forces to the change in emissions in Chinese megalopolises over the 1985–2010 period. It will be beneficial for formulating urban planning and emissions reduction policies at the city level in China.

The decomposition approach has been widely used to quantify the impact of different drivers of energy consumption and CO_2 emissions (Guan et al. 2008; Raupach et al. 2007). Within the literature, two well-known decomposition methods, namely, structural decomposition analysis (SDA) and index decomposition analysis (IDA), have been widely used to analyze the driving factors due to their adaptability and simplicity (Liu et al. 2012b). The SDA method is based on input-output tables and has the advantages of being able to distinguish a range of production effects and the final demand effects in the changes in energy demand as well as CO_2 emissions. However, a major challenge to using this method at the city scale is the lack of input-output tables, and therefore, it is mainly used for national evaluations (Feng et al. 2012; Guan et al. 2008). IDA is developed based on index theory (Ang 2004). It topically uses aggregated data in a period-wise or time series manner, having the advantage of analyzing how the drivers have evolved over time (Liu et al. 2012a). Although IDA is only capable of capturing the impacts of direct energy consumptions, this approach has gained some favorable momentum in recent years due to readily available data and the flexibility of application to disaggregation at different levels, which facilitate empirical application and comparisons (Wang et al. 2011; Zhao et al. 2012). There is no consensus between them regarding which is better decomposition method. Moreover, the scope of this paper is to quantify the contributions of each driving factor to the CO_2 emissions in Chinese megalopolises, in addition to evaluating the best choice or developing a new decomposition technique. Thus, we use the IDA method to explore the impacts of the drivers over the studied period, due to the readily available data set at the city scale and sufficient ability of this method.

Among the few studies on the trajectories and the driving forces of CO_2 emissions in Chinese cities, there are two main limitations. First, most previous studies focus on the effects of economic growth and energy intensity, ignoring the impacts of expanding urban areas on CO_2 emissions. The energy demand caused by the infrastructure construction and the associated changes in income and lifestyle are most likely the most significant factors in determining the increase in energy consumption in the course of urbanization in China (Feng et al. 2012; Ma 2015). China is now in the process of rapid urbanization, and only a few empirical studies examining the impacts of urbanization on CO_2 emissions have been conducted at the city level. Second, among these few empirical works, most of those are conducted for one single city, e.g., Beijing (Yu et al. 2015), Tianjin (Kang et al. 2014; Shao et al. 2014), and Suzhou (Wang et al. 2014a). Thus, the comparison of driving forces between different cities or megalopolises is thus limited.

This study is different from previous studies in two aspects. First, we examine the impacts of expanding urban areas and other driving forces on the increasing CO_2 emissions. The urbanization effect in this paper is defined as expanding urban areas and changes in population density. Second, this study employs a city-level energy data set that is developed by a downscale model to explore the differences in total emissions and their drivers among ten megalopolises in China. Due to the significant contributions of the industry sector to total emissions and the data availability, we further decompose the industry emissions into 35 sub-industries in the Pearl River Delta in southern China to capture the drivers of CO_2 emissions in its industry system.

Methodology and data

Investigated areas

This study focuses on ten megalopolises located from western to eastern China (Fig. 1), where the major portion of the economic activity and urbanization has occurred. There are 95 prefecture-level cities (cities hereafter, referring to the administrative units that come after the provincial level but before the county level) in total (Table 1). To examine the precise role of urban areas in addressing CO_2 emissions, we pay close attention to the urbanized and urbanizing areas ("urban areas," hereafter) defined by the nighttime light imagery in our previous study (Meng et al. 2014), not the entire administrative areas, which include urban and rural areas. The employed nighttime light imagery is operated by the Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) and is published annually by the National Oceanic and Atmospheric Administration (NOAA 2010). Based on this definition, the urban areas increases by 3.4 times by the end of 2010, reaching up to 191,496 km^2 (sq. km, hereafter). Despite the relatively small areas compared with the national territory in China, the urban areas in the ten megalopolises are home to 38% of the national population, and produce 64% of national GDP in 2010. Accordingly, the total energy consumption in the ten megalopolises reaches 40.0 EJ in 2010, which contributes to 43% of the total energy consumption in China. That is, overall, the energy intensity in the ten megalopolises is lower than that at the national level.

Estimation of CO_2 emissions

Both the total CO_2 emissions and the sectoral emissions, namely, from the industry, construction, transportation, and service sectors, are estimated in this study. We exclude emissions from agriculture by assuming that they are produced outside of urban areas. To avoid double counting, the estimation principle lies in the scope 2 proposed by Local Governments for Sustainability (ICLEI) (2010). That is, the energy

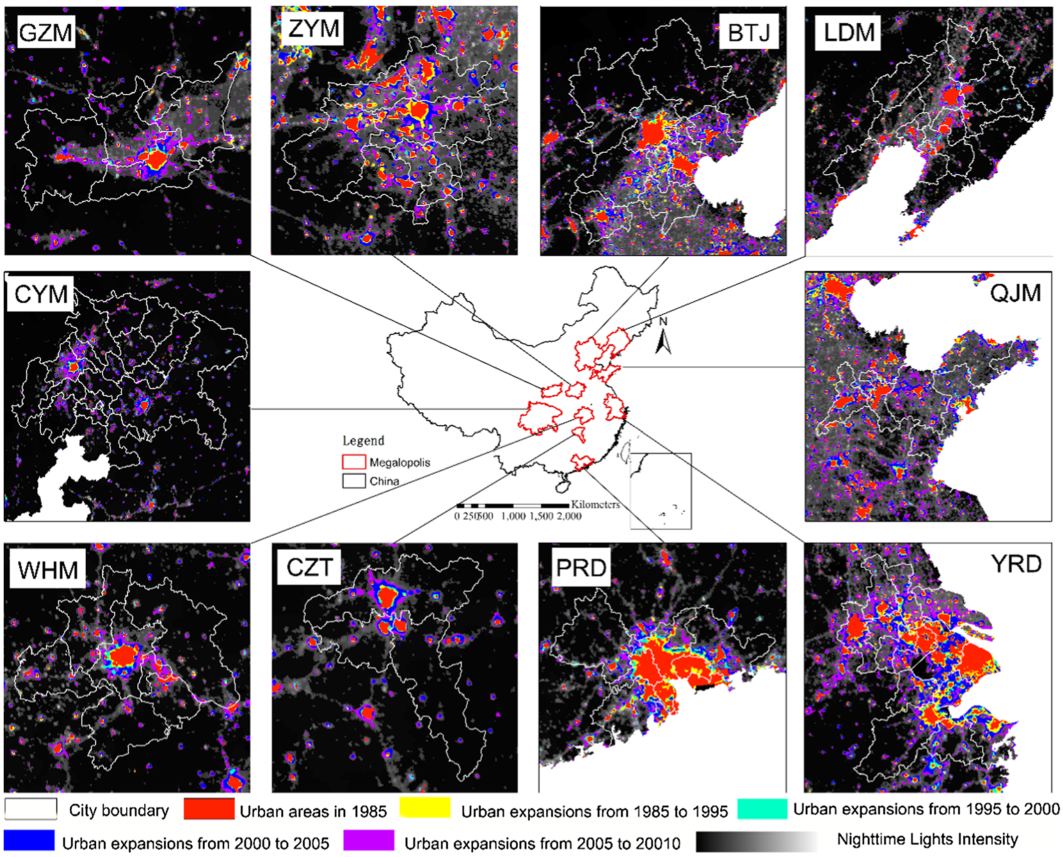


Fig. 1 Urban areas (urbanized and urbanizing areas mapped by nighttime light imagery) of the ten megalopolises in China. The full names of the ten megalopolises' codes are defined in Table 1. *Data sources:* NOAA (2010) and authors' previous work (Meng et al. 2014)

Table 1 Cities within the ten Chinese megalopolises

Code	Megalopolis	Cities
Coastal megalopolis		
YRD	Yangtze River Delta	Shanghai, Nanjing, Wuxi, Changzhou, Suzhou, Nantong, Yangzhou, Zhenjiang, Taizhou, Hangzhou, Ningbo, Jiaxing, Huzhou, Shaoxing
BTJ	Beijing-Tianjin-Heibei Megalopolis	Beijing, Tianjin, Shijiazhuang, Tangshan, Qinhuangdao, Baoding, Zhangjiakou, Chengde, Cangzhou, Langfang
PRD	Pearl River Delta	Guangzhou, Shenzhen, Zhuhai, Foshan, Jiangmen, Zhaoqing, Huizhou, Dongguan, Zhongshan
QJM	Qingdao-Jinan Megalopolis	Jinan, Qingdao, Zibo, Dongying, Yantai, Weifang, Weihai, Rizhao
LDM	Liao-Dong Megalopolis	Shenyang, Dalian, Anshan, Fushun, Benxi, Dandong, Jinzhou, Yingkou, Fuxin, Liaoyang, Panjin, Tieling, Huludao
Inland megalopolis		
CYM	Cheng-Yu Megalopolis	Chongqing, Chengdu, Zigong, Luzhou, Deyang, Mianyang, Guangyuan, Suining, Neijing, Leshan, Nanchong, Meishan, Yibin, Guangan, Dazhou, Yaan, Bozhong, Ziyang
ZYM	Zhong-Yuan Megalopolis	Zhengzhou, Kaifeng, Luoyang, Pingdingshan, Xinxiang, Jiaozuo, Xuchang, Luohe
GZM	Guan-zhong Megalopolis	Xian, Tongchuan, Baoji, Xianyang, Weinan
WHM	Wu-Han Megalopolis	Wuhan, Huangshi, Ezhou, Xiaogan, Huanggang, Xianning, Qianjiang, Tianmen, Xiantao
CZT	Changsha-Zhuzhou-Xiangtan Megalopolis	Changsha, Zhuzhou, Xiangtan

consumed within the specific province, except for thermal power and heat generation, is used to calculate the CO_2 emissions in this study, and the energy used for thermal power and heat generation is allocated to the place where it is consumed. The calculation approach proposed by the Intergovernmental Panel on Climate Change (IPCC) is used in this study (IPCC 2006). The corresponding emission factors are obtained from the *Guidelines for the Provincial Greenhouse Gas Emissions Inventories* (NDRC 2011).

$$F = \sum_i \sum_j F_{ij} = \sum_i \sum_j E_{ij} \times CF_j \times EF_j \times OF_j \quad (1)$$

where F_{ij} denotes the provincial CO_2 emissions emitted from fossil fuel E_j in sector i (million ton carbon, MtC hereafter), CF is the conversion factors from the physical unit to the lower heating value (TJ/physical unit), which is reported annually by the NBSC (1986–2009a, b, c), EF_i is the carbon emissions factor of fossil fuel j (ton C/TJ), and OF_i is the oxidation factor (%) used to account for the fraction of the potential carbon emitted to the atmosphere after combustion.

It is important to know that the variations in the energy sources used for thermal power and heat generation cause annual changes in the emission factors for thermal power and heat. Given that the distributions of electricity between cities are missing, the emissions factors of power grids are used to calculate the CO_2 emissions from electricity consumption in urban areas. Currently, the power grid in China is divided into seven sub-grids, and each has its own annual emission factors. We calculate them based on provincial energy balance tables, using the method proposed by the National Development and Reform Commission (2010).

$$\mathrm{EF}_{grid,y} = \sum_j \left(E_{j,y} \times \mathrm{CF}_{j,y} \times \mathrm{EF}_j \right) \Big/ \mathrm{EG}_y \quad (2)$$

where $\mathrm{EF}_{\mathrm{grid},y}$ is the regional grid emissions factor in year y, $E_{i,y}$ is the combustion of fuel j for thermal power generation, and EG_y is the net production of electricity (including the primary and secondary electricity) in a regional-specific power grid. CF and EF represent as the same variables as in Eq. (1). The annual emissions factors of heating are then calculated by the same method as that used for thermal power, assuming that there is no transfer of heating between provinces (Kang et al. 2014).

Once the calculations on provincial energy consumption and CO_2 emissions are completed, the energy consumption and CO_2 emissions within urban areas are estimated by a downscale model, using DMSP/OLS data as proxies for energy consumption and the related emissions. The calculation methods and the downscale model have already been discussed in our previous paper (Meng et al. 2014). The basic idea of this model is a linear relationship between the sum of nighttime light intensity and energy consumption. The validity of the downscale model is given at Appendix A:

$$F_c = F_p \times \left(\frac{\hat{F}_c}{\hat{F}_p} \right) = F_p \times \frac{\left(\alpha \times \mathrm{NTL}_c + \beta_p + \varepsilon \right)}{\left(\alpha \times \mathrm{NTL}_p + \beta_p + \varepsilon \right)} \quad (3)$$

where F_c is the estimated CO_2 emissions in the urban areas of a specific city, F_p is the provincial CO_2 emissions calculated by Eq. (1), and $\hat{F}_c$and $\hat{F}_p$are the estimated urban and provincial CO_2 emissions by nighttime light data, respectively. NTL is the sum of nighttime lights within the defined urban areas. α is the slope of the linear function between CO_2 emissions and nightlight lights, β is the province-fix coefficient for capturing the differences between provinces, and ε is the error term. All the three coefficients are estimated from the provincial panel data set.

Index decomposition analysis

IDA is used to quantify the contributions of drivers of CO_2 emissions in Chinese megalopolises. To capture the contributions of CO_2 emissions from the booming economic growth and urbanization in Chinese megalopolises, we decompose the CO_2 emissions into four factors: the urbanization level, the economic scale, energy efficiency, and the energy structure. The decomposed formula may be written as follows:

$$F = \sum_i F_i = \sum_i A \left(\frac{P}{A} \right) \left(\frac{G}{P} \right) \left(\frac{G_i}{G} \right) \left(\frac{E_i}{G_i} \right) \left(\frac{F_i}{E_i} \right) = \sum_i Adgs_i e_i f_i \quad (4)$$

where F is the total CO_2 emissions (MtC) from a specific megalopolis, and F_i is the CO_2 emissions from sector i (industry, construction, transportation, and service). A is the amounts of urban areas (km^2), P is the urban population (million person), $d = (P/A)$ is the urban density (person/km^2), G is the GDP (million 2000 U.S. dollar, \$), and G_i is the industry value added of sector i. Therefore, $s_i = (G_i/G)$ is the economic structure (%), E is the total energy consumption (TJ), $e_i = (E_i/G_i)$ is the energy intensity (MJ/\$) of sector I, and $f_i = (F_i/E_i)$ is the carbon intensity (gC/MJ) of energy in sector i.

To further investigate the contributions of CO_2 emissions from different sub-industry sectors, we decompose the CO_2 emissions from the industry sector (F_{ind}) into 36 sub-industries:

$$F_{\text{ind}} = \sum_j F_j = \sum_j G_j \left(\frac{E_j}{G_j}\right)\left(\frac{F_j}{E_j}\right) = \sum_j G_j e_j f_j \qquad (5)$$

where j is the sub-industries, which are classified from the industry sector according to the National Economy Industry Classification Standard (GB/T 4754–2002) and summed up to 36 sub-industries; F_{ind} is the CO_2 emissions from the industry sector, and F_j is the CO_2 emissions from the j-th sub-industry. G and E represent as the same variables in j-th sub-industry as those in Eq. (4).

Following Ang (2005), the LMDI (logarithmic mean Divisa index) method was used to calculate the relative contributions of the driving factors. Changes in the CO_2 emissions from year 0 to year T are decomposed as follows:

$$\Delta F = F^T - F^0 = \Delta F_A + \Delta F_d + \Delta F_g + \Delta F_s + \Delta F_e + \Delta F_f \qquad (6)$$

where

$$\Delta F_A = \frac{F^T - F^0}{\ln F^T - \ln F^0} \ln \frac{A^T}{A^0} \qquad (7)$$

$$\Delta F_d = \frac{F^T - F^0}{\ln F^T - \ln F^0} \ln \frac{d^T}{d^0} \qquad (8)$$

$$\Delta F_g = \frac{F^T - F^0}{\ln F^T - \ln F^0} \ln \frac{g^T}{g^0} \qquad (9)$$

$$\Delta F_s = \sum_i \frac{F_i^T - F_i^0}{\ln F_i^T - \ln F_i^0} \ln \frac{s_i^T}{s_i^0} \qquad (10)$$

$$\Delta F_e = \sum_i \frac{F_i^T - F_i^0}{\ln F_i^T - \ln F_i^0} \ln \frac{e_i^T}{e_i^0} \qquad (11)$$

$$\Delta F_f = \sum_i \frac{F_i^T - F_i^0}{\ln F_i^T - \ln F_i^0} \ln \frac{f_i^T}{f_i^0} \qquad (12)$$

In Eq. (7)–Eq. (12), ΔF represents the changes in CO_2 emissions from year 0 to year T. ΔF_A and ΔF_d, ΔF_g, ΔF_s, ΔF_e, and ΔF_f denote the contributions of the urbanization, economy, energy intensity, and carbon intensity factors, respectively. The same method is used to decompose the CO_2 emissions from industry energy consumption, which yields three driving factors (ΔF_G, ΔF_e, and ΔF_f). The positive contributions indicate the driving effects on CO_2 emissions, and the negative contributions indicate the decoupling effects on CO_2 emissions.

To classify the different driving effects on the changes in CO_2 emissions in Chinese megalopolises, the six drivers are grouped into three categories based on the fairly similar characteristics of the variables. That is, urban areas (A) and urban density (d) are grouped as the urbanization effect, per capita GDP (g) and economic structure (s) are the economic effect, and the energy intensity of GDP (e) and the carbon intensity of energy (f) are the intensity effect.

Data

The research period spans from 1985 to 2010, when the rapid economic growth and urbanization in China occurred. The energy data are obtained from the provincial energy balance tables published in the *China Energy Statistical Yearbook* (NBSC 1986–2011a, b, c). The energy balance table expresses both the sources of supply for each energy type and their uses (including the uses for transformation, distribution loss, and final consumption) by physical unit in a single column. The final energy consumption data are also divided into six sectors, namely, the agricultural, industry, construction, transportation (transport, storage, and postal service), service (wholesale, trade, and hotel, restaurants), and residential consumption and other sectors. In this study, we only calculate four sectors, namely, the industry, construction, transportation, and service sector consumption.

Because the industry sector is the major contributor to CO_2 emissions in urban China (Meng et al. 2014), we further divide the industry sector into 36 sub-sectors according to the *National Economic Industry Classification Standard* (*GB/T 4754–2002*) and the presence of the sub-sectors in the studied megalopolises. Due to data limitations, we decomposed the emissions in the industry sector in the PRD from 2000 to 2010. Both the energy consumption data and the value added of each sub-industry in the PRD are obtained from the *Guangdong Statistical Yearbook* (NBSC 2001, 2011).

The population and economic data in prefecture cities are accessed from the *China City Statistical*

Yearbook (NBSC 1986–2011a, b, c) and provincial statistical yearbook. The GDP data are deflated to 2000 constant price (CNY) and then to 2000 U.S. dollars ($) by the average exchange rate (1 US$ = 8.28 CNY) in 2000. Note that both the population and economic data are reported at the level of the administrative unit (city-level here), which are downscaled to the urban scale by the downscale model using nighttime light as a proxy, assuming that both the population and economic activities are highly correlated with the nighttime light intensity (Henderson et al. 2012).

The summary statistics for the variables used in this study are presented in Table 2. Measured by the mean value of the standard deviation of each variable, the total CO_2 emissions (F), urban areas (A), and energy intensity (e) of all four sectors show great variations across the ten megalopolises in China. From 1985 to 2010, both the urban areas (A) and per capital GDP (g) demonstrate rapid growth trends in the ten megalopolises, with annual growth rates of 5.02 and 10.37%, respectively. Overall, urban density overall increases slightly over the studied period, with an annual growth rate of 0.3%. The energy intensity of all the four sectors presents a downward trend on average, and the energy intensity of the industry sector experiences the fastest decline with an annual rate of −3.95%. The largest of variation in the economic structure occurs in the transportation and service sectors, the share of which overall increase over the examined period. The economic share of the industry sector, which is the dominant sector across the ten megalopolises in China, shows less variation over the examined period.

Results

In this section, we first analyze the uncertainty induced by the data set as well as the methods used in this study. Then we examine the patterns of CO_2 emissions, both the total and sectoral emissions, from urban China in the years of 1985, 1995, 2000, 2005, and 2010. Finally, we analyze the quantified contributions of each driver to the growth in CO_2 emissions over the studied period.

Uncertainty analysis

Before presenting the results shown by this study, we will firstly analyze the uncertainty raised by the data as well as the method used in this study. We access the official data, mainly energy and economic data, from the NBSC (1986–2011a, b, c). Several scholars have been questioning the data transparency and accuracy of statistics (Chan 2007; Guan et al. 2012). It is estimated that Chinese CO_2 emissions may be off by as much as 20%

Table 2 Summary statistics

Variable	Measures	Unit	Mean	Std. D.	Min	Max	Obs.
F	Total CO_2 emissions	MtC	33.14	38.80	1.70	195.51	50
A	Urban areas	km^2	11,281	10,736	732	51,228	50
d	Urban density	Person/km^2	1354	435	796	2493	50
g	Per Capital GDP	$/person	1832	1695	222	7718	50
s_{ind}	The economic share of industry sector	%	40.39	6.83	30.75	57.7	50
s_{con}	The economic share of construction sector	%	5.88	1.36	2.88	10.98	50
s_{tran}	The economic share of transportation sector	%	5.69	1.75	1.9	10.11	50
s_{serv}	The economic share of service sector	%	29.88	8.19	16.5	47.62	50
e_{ind}	The energy intensity of industry sector	MJ/$	69.52	43.95	2.23	210.34	50
e_{con}	The energy intensity of construction sector	MJ/$	12.22	11.79	1.72	55.63	50
e_{tran}	The energy intensity of transportation sector	MJ/$	59.12	45.06	0.56	196.44	50
e_{serv}	The energy intensity of service sector	MJ/$	6.08	7.12	0.21	34.46	50
f	The carbon intensity of energy	gC/MJ	22.05	2.31	9.37	31.8	50

All the price data are converted to the 2000 constant price (CNY) and then to 2000 U.S. dollar ($) by the average exchange rate (1 US$ = 8.28 CNY) in 2000 and that coal consumption accounts for 71% of the emissions discrepancy (Guan et al. 2012). Moreover, the aggregated provincial energy consumption has exceeded the national data since 1997 by as much as 18% higher in 2010 (Guan et al. 2012). We use the provincial energy balance tables, which are the upper bound of all reported amounts in China, to estimate CO_2 emissions. Despite the deviation in the Chinese energy data, without the ideal data, the data published by the NBSC remain the starting point for the statistics published by many international institutions (e.g., IEA, Lawrence Berkeley National Laboratory, and so on). Thus, using the official energy balance tables in the analysis is appropriate.

On the economic side, both the GDP statistics and per capita GDP have come under increasing criticism (Chan 2007). The "performance-assessment" function of these indicators inevitably introduces error into the data. The GDP statistics reported by local governments have regularly exceeded those of the central government, by as much as 9% in 2010 (Casey and Koleski 2013). Thus, the amount of the energy intensity of GDP (e) may contain a large bias, and the urban per capita GDP (g) may be overestimated due to the underestimated urban population (P). In other words, considering the inaccuracy and inconsistent statistical population data in China, the potential contribution of urbanization to increasing CO_2 emissions may be larger than the results we report here, whereas the effect of economic growth may be smaller, additionally, the role of the energy intensity of GDP in decoupling the emission growth may not be as significant as we report. New regulations have been issued by the Chinese government to combat statistical corruption (Wang and Chen 2010), promising that more reliably data will address this issue in the future.

In addition to the uncertainty of the statistical data, it is important to bear in mind that we focus on the dynamic urban areas in this study, not the entire administrative areas. Data uncertainty thus arises through the construction of constant data series at an urban scale, which is a widely accepted method for downscaling socioeconomic parameters and CO_2 emissions by night-time light data (Henderson et al. 2012). Moreover, a validity test has been conducted in a previous study to validate the reliability of the downscale model when used in urban China (Meng et al. 2014), which is also given in Appendix A, proving its ability to downscale both the total fuel emissions and the sectoral emissions from the provincial level to the urban scale.

Methodological uncertainty may also be significant but is often difficult to quantify. We use the LDMI decomposition method to quantify the impacts of booming economic growth and urbanization on the growing CO_2 emissions, due to its theoretical foundation, adaptability, and ease of use and result interpretation (Ang 2004). Although it is being a preferred method in energy-related CO_2 emissions decomposition, the quality and validity of the decomposition results are largely affected by the level of data aggregation and the choice of decomposed variables. Because the variable selection can be problem specific, the quantified effects of each variable on CO_2 emissions may simply be generated differently by different governing formulas. This phenomenon also leads to bias in cross-study comparisons. The quantified contributions of the variables are thus case-specific.

Patterns of CO_2 emissions from urban China

A sharp acceleration in CO_2 emissions has occurred since 2000 (Fig. 2). CO_2 emissions increase by 749 MtC from 1985 to 2010 (from 117 to 866 MtC) in the ten megalopolises, with 84% of those increases occurring in the post-2000 period. The annual growth rate in CO_2 emissions from the ten megalopolises is 4.7% for the 1985–2000 period, whereas for the 2000–2010 period, the growth rate increases to 14.0%. The patterns of CO_2 emissions from the different megalopolises are very similar. The YRD, the most developed megalopolis in China, contributes 9.3% of national cumulative emissions from 1985 to 2010. Following the YRD, the BTJ megalopolis accounts for 7.2% of the national

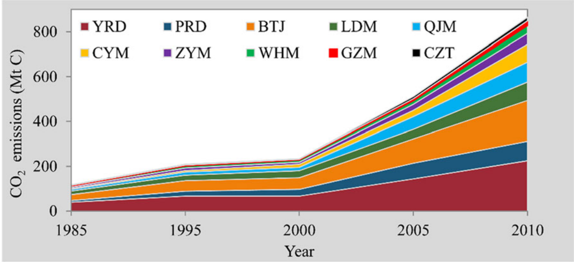


Fig. 2 CO_2 emissions from the ten megalopolises in China. The full names of the ten megalopolises' codes are defined in Table 1. Data source: *China Energy Statistical Yearbook* (*1986–2011*) and authors' calculations

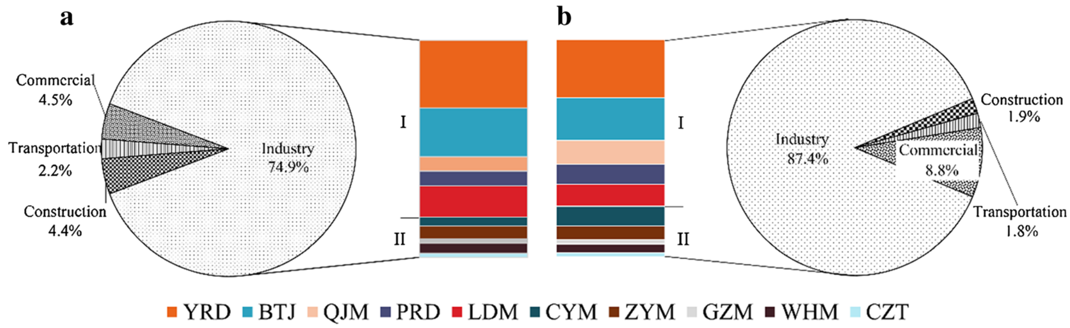


Fig. 3 The proportions of sectoral emissions in ten megalopolises in China. **a** sectoral emissions in 1985 and **b** sectoral emissions in 2010. *I* denotes the megalopolises located in the coastal region and *II* denotes those located in the inland region. The full names of the ten megalopolises' codes are defined in Table 1. Data source: *China Energy Statistical Yearbook* (*1986–2011*) and authors' calculations

cumulative emissions during the same period. The PRD, LDM, and QJM, which are located in the coastal region of China, contribute 3.8, 3.4, and 3.1% of national cumulative emissions over the 1985–2010 period, respectively. The other five megalopolises, located in the inland region of China, represent a total of 6.7% of national cumulative emissions in the 1985–2010 period.

A breakdown of emissions among sectors is displayed in Fig. 3. Of the various sectors, the industry sector is the largest contributor to the total emissions in Chinese megalopolises, accounting for 74.9–87.4%, with an increase from 74 MtC in 1985 to 597 MtC in 2010. Over 50% of the CO_2 emitted by the industry sector originates from the YRD, the PRD, and the BTJ, the regions with the strongest economic strength and vitality in China. The CO_2 emitted by the industry sector in the inland regions increases from 14 MtC in 1985 to 138 MtC in 2010. This increase is explained by the growth in energy-intensive industries in western China since 2000 (NBSC 2011). The share of the other three sectors' emissions is relatively small. Construction emissions increase from 4 MtC in 1985 to 13 MtC in 2010, playing a relatively small role in the total emissions. Note that we only calculated the direct emissions induced by the construction activities, whereas the emissions from material production such as steel and cement used for constructions are calculated in the industry sector. The share of the transportation sector in total emissions decreases slightly over the studied period, from 2.2% (2 MtC) in 1985 to 1.8% (13 MtC) in 2010. Different from the emissions in the aforementioned two sectors, the share of emissions in the service sector almost doubles, from 4.5% (4 MtC) in 1985 to 8.8% (60 MtC) in 2010. The contributions of various sectors to the total emissions are similar to the other cities in China, such as Suzhou (Wang et al. 2014b) and Tianjin (Kang et al. 2014).

Different from the urban per capita emissions in developed countries, the per capita emissions from the Chinese megalopolises are higher than the national averages (Fig. 4). The YRD, which has the largest contribution of CO_2 emissions, is in the middle level of per capita emissions. The largest per capita emissions arise in the LDM, which lies in north-eastern China and consumes more energy for heating in winter, whereas the PRD holds the smallest per capita emissions, which are close to the national averages, due to the labor-intensive economic structures. A significant decrease

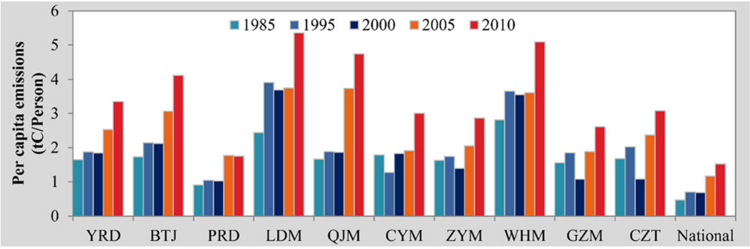


Fig. 4 Per capita carbon emissions in ten Chinese megalopolises, 1985–2010. The full names of the ten megalopolises' codes are defined in Table 1. Data source: *China City Statistical Yearbook*, *China Energy Statistical Yearbook* and authors' calculations

in the per capita emissions in some inland megalopolises emerges in 2000, because both the energy consumption and total emissions decrease slightly but the population continues to grow during the 1995–2000 period. Overall, the per capita CO_2 emissions in coastal megalopolises are higher than those in inland megalopolises, due to the higher urbanization level associated with changes in income level, lift style, etc. The values of nationwide per capita emissions are low relative to the urban per capita values, 0.47 tC/Person in 1985 and 1.52 tC/Person in 2010. However, the gaps between the urban per capita emissions and the national averages have gradually narrowed over the 1985–2010 period, from 3.6 to 2.2 times, respectively. This notion is supported by empirical analyses that indicate a convergence of per capita CO_2 emissions in urban China (Huang and Meng 2013).

The contributions of drivers to CO_2 emissions in Chinese megalopolises

We then divide the research period into two sub-periods (1985–2000 and 2000–2010) based on the different trends of CO_2 emissions in these two periods. The quantitative contributions of each driver over the two sub-periods are calculated by Eq. 7 –Eq. 12. Figure 5 provides the decomposition results in cumulative terms.

As shown in Fig. 5, the YRD, the BTJ, and the PRD are the three largest contributors to the cumulated contributors to the changes in CO_2 emissions in the 1985–2000 period, accounting for 66% of the total changes in the ten megalopolises. The PRD presents the largest annual change rate in CO_2 emissions, equaling to 9% in the same period, due to the rapid economic growth in Guangdong Province since 1980. In the post-2000 period, the YRD, the BTJ, and the LDM become the three largest contributors, contributing 52% of the total changes in the ten megalopolises. Despite the small amounts of changes in total emissions in the inland megalopolises, overall, they present a larger annual change rate in the post-2000 period, due to the rapid increases in the CO_2 emissions in the inland megalopolises.

The economic effect

The contributions of economic growth (g) and the economic structure (s) are regarded as the economic effects on the increasing CO_2 emissions. Unsurprisingly, economic growth (g) is the largest driver of the increasing CO_2 emissions of the past 25 years. The increase in economic growth contributes 615 MtC (75.9% of the total emissions) of CO_2 emissions in the ten megalopolises from 1985 to 2010, with 71% of the increasing CO_2 emissions occurring in the post-2000 period (Fig. 5). The driving effects of economic growth in the YRD, the PRD, and the BTJ are even stronger, explaining 71.7% (441 of 615 MtC) of the increasing CO_2 emissions induced by economic growth (g). The reason is the significantly higher per capita GDP (g) in these megalopolises compared with the others (Fig. 6). The CYM, the economic engine of the inland regions, contributes 34 MtC CO_2 over the past 25 years, with over 90% (31 MtC) occurring in the post-2000 period.

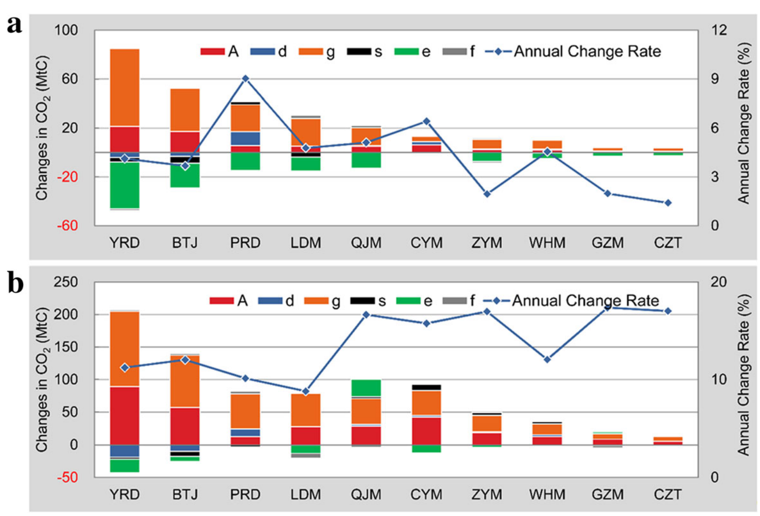


Fig. 5 Cumulative contributions of drivers to the change of CO_2 emissions in Chinese megalopolises over two sub-periods. **a** Changes in CO_2 emissions from 1985 to 2000 and **b** changes in CO_2 emissions from 2000 to 2010. The full names of the ten megalopolises' codes are defined in Table 1. Data source: *China City Statistical Yearbook (1986–2011)*, *China Energy Statistical Yearbook* (*1986–2011*), and authors' calculations

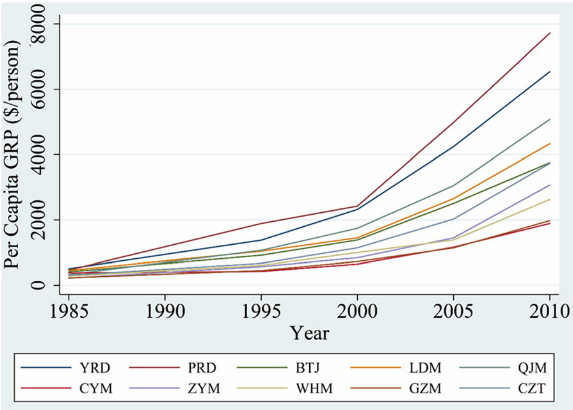


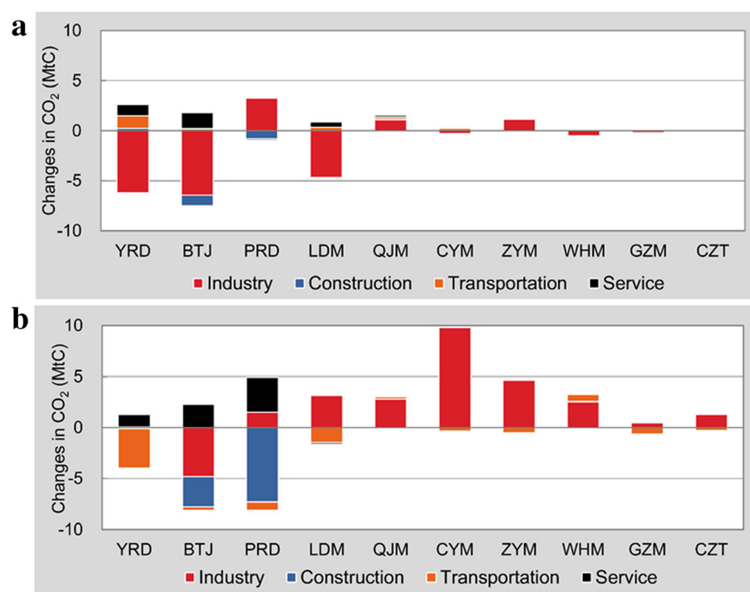
Fig. 6 Per capita GDP in ten megalopolises from 1985 to 2010. The full names of the ten megalopolises' codes are defined in Table 1. The price values are converted to 2000 constant prices (CNY) and then to 2000 U.S. dollars ($) by the average exchange rate (1 US$ = 8.28 CNY) in 2000. Data source: *China City Statistical Yearbook* (*1986–2011*), provincial statistical yearbooks, and authors' calculations.

Despite the smaller value of CO_2 in the CYM than those in coastal megalopolises, the economic growth in the CYM is the largest contributor to the CO_2 emissions in the inland megalopolises, due to its leading role in the economy of the inland regions (Fig. 6).

Different from the significant driving effect of economic growth, the change in the economic structure plays a minor role in the increasing CO_2 emissions, with the industry sector maintaining a dominant role in the regional economic system over the entire studied period. Overall, the economic structure adjustment only offsets 8 MtC CO_2 from 1985 to 2000 but adds 9 MtC to the increasing CO_2 emissions in the post-2000 period. To unfold the structural changes among the four economic sectors, we further show the individual contributions of the changes in the four economic sectors, namely, the industry, construction, transportation, and service sectors, in Fig. 7, distinct from the cumulated contributions as shown in Fig. 5. Clearly, the increasing share of the industry sector in the economic system in the megalopolises, except the YRD, the BTJ, and the LDM, makes a positive contribution to the CO_2 emissions, adding 8.6 MtC CO_2 (334% of the net changes due to the structural effect) from 1985 to 2010.

On the one hand, the shares of the industry sector in the BTJ continuously decrease over the studied period, from 49 to 35%, offsetting 11.3 MtC CO_2. The decreasing share of the industry sector in the economy of the BTJ is mainly caused by the policy-dominated adjustment in Beijing. In the YRD and the LDM, the shares of the industry sector first decrease by 9 and 14% from 1985 to 2000, then increase slightly (0.02% in the YRD and 3% in the LDM) in the post-2000 period. The decrease in the industry share in the YRD is caused by the economic development, from an industry-dominant to a service-dominant stage. The significant decrease in the LDM, however, is because numerous state-owned enterprises fell into decay or even shut down in the 1990s. The both decreases in the industry sector in

Fig. 7 The contributions of the changes in the economic structure to the changes of CO_2 emissions in Chinese megalopolises. **a** Changes in CO_2 emissions from 1985 to 2000 and **b** changes in CO_2 emissions from 2000 to 2010. The full names of the ten megalopolises' codes are defined in Table 1. *Data source*: China City Statistical Yearbook and authors' calculations



both the YRD and the LDM offsets 10.9 MtC emissions. On the other hand, the other seven megalopolises contribute 27.5 MtC emissions due to the increase in the share of the industry sector in the economic system. The booming industrial growth in the CYM, the most active market in inland China, contributes 9.8 MtC emissions during the post-2000 period. Overall, the construction and transportation sectors, overall, offset 11.7 MtC and 4.7 MtC emissions in the Chinese megalopolises during the studied period, and the increasing share of the construction and transportation sectors in the BTJ and the PRD make the largest contribution. Overall, the share of the service sector in the economy continually increases, contributing 10.4 MtC emissions. The most significant increases are found in the YRD, BTJ, and PRD megalopolises, the most developed regions in China. The findings present a picture in which China is in the process of reducing the carbon economy, transforming from industry dominated to industry-service dominated.

A more disaggregated sub-sector decomposition analysis is further performed for the industry sector in the PRD from 2000 to 2010 (Fig. 8). The booming industrial growth (G) is also the leading cause of the increasing CO_2 emissions in the industry sector in the PRD, which contributes to 136 MtC emissions throughout the studied period. Six energy-intensive industries, namely, *Petroleum Refining, Coking and Nuclear Fuel Processing* (Industry Code 25), *Manufacture of Raw Chemical Materials and Chemical Products* (Industry Code 26), *Nonmetal Mineral Products* (Industry Code 31), and *Smelting and Pressing of Ferrous Metals* (Industry Code 32). *Smelting and Pressing of Nonferrous Metals* (Industry Code 33) and *Production and Supply of Electric Power and Heat Power* (Industry Code 44) contribute to approximately 54% of the increasing CO_2 emissions due to the growing industry output (G). The largest industry output in the PRD is the *Manufacture of Communication Equipment, Computers and Other Electronic Equipment* (Industry Code 40); however, its contribution to the increasing CO_2 emissions is minor due to its relatively small growth rate over the examined period. Except for the large positive effect from industry output (G), overall, the adjustment in the industry structure (s) is overall a minor, and negative contributor, offsetting 2.5 MtC emissions from 2000 to 2010. The reduction is mainly caused by the notable shift in the share of the *Production and Supply of Electric Power and Heat Power* (Industry Code 44) in the total industry output, which decreases from 10.5% in 2000 to 5.8% in 2010. This remarkable adjustment offsets 7.2 MtC (9% of the total increases) emissions. However, the structural changes

Fig. 8 Cumulative contributions of drivers to the change in CO_2 emissions from the industrial sub-sectors in the PRD from 2000 to 2010. The abscissa figures represent the industry code, which are as follow: *07* Extraction of Petroleum and Natural Gas; *08* Mining and Dressing of Ferrous Metal Ores. *09* Mining and Dressing of Nonferrous Metal Ores; *10* Mining and Dressing of Nonmetal Ores; *13* Processing of Farm and Sideline Food; *14* Manufacture of Food; *15* Manufacture of Beverage; *16* Tobacco Products; *17* Textile Industry; *18* Manufacture of Textile Garments, Footwear and Headgear; *19* Leather, Fur, Feather, Down and Related Products; *20* Timber Processing, Bamboo, Cane, Palm Fiber & Straw Products; *21* Manufacture of Furniture; *22* Papermaking and Paper Products; *23* Printing and Record Medium Reproduction; *24* Manufacture of Cultural, Educational and Sports Articles; *25* Petroleum Refining, Coking and Nuclear Fuel Processing; *26* Manufacture of Raw Chemical Materials and Chemical Products; *27* Manufacture of Medicines; *28* Manufacture of Chemical Fibers; *29* Rubber Products; *30* Plastic Products; *31* Nonmetal Mineral Products; *32* Smelting and Pressing of Ferrous Metals; *33* Smelting and Pressing of Nonferrous Metals; *34* Metal Products; *35* Manufacture of General-purpose Machinery; *36* Manufacture of Special-Purpose Machinery; *37* Manufacture of Transport Equipment; *39* Manufacture of Electrical Machinery and Equipment; *40* Manufacture of Communication Equipment, Computers and Other Electronic Equipment; *41* Manufacture of Instruments, Meters and Machinery for Cultural and Office Use; *42* Handicraft and Other Manufactures; *44* Production and Supply of Electric Power and Heat Power; *45* Production and Supply of Gas; *46* Production and Supply of Water. *Data sources*: *Guangdong Statistical Yearbook* (*2001, 2011*) and authors' calculations

in the other four energy-intensive industries, namely *Petroleum Refining, Coking and Nuclear Fuel Processing* (Industry Code 25), *Manufacture of Raw Chemical Materials and Chemical Products* (Industry Code 26), *Smelting and Pressing of Ferrous Metals* (Industry Code 32), and *Smelting and Pressing of Nonferrous Metals* (Industry Code 33), are dominant positive contributors, driving up the emissions by 5.5 MtC. These results are consistent with those of Kang et al. (2014), who find that constant economic growth is the leading cause of the carbon emissions increases in the industry sector and that the share of energy-intensive industry continuously increased in Tianjin, China, from 2001 to 2009.

The urbanization effect

The urbanization effect, including the expanding of urban areas (A) and changes in urban density (d), is the second largest contributor to the increasing CO_2 emissions over the studied period, playing a more important role in the recent period. The urban areas, in the ten megalopolises, increased by 3.4 times, over the studied period, reaching up to 194,185 km^2 at the end of 2010. The expanding urban areas results in a 369 MtC increase (44% of the total increase) relative to 1985, with 82% occurring in the post-2000 period. The largest driving effect of the expanding urban areas on CO_2 emissions is present in the YRD, the BTJ, and the CYM. Over 50% of the total increases are driven by the expanding urban areas in the three megalopolises. The reason is the YRD and BTJ are, respectively, are the economic and political centers of China, attracting thousands of people every year (Zhao 2005), and the CYM is the region with the most active economy in inland China (NBSC 2011). Continuously migrating people and economic activities expand the urban areas, resulting in more CO_2 emissions.

Both the growing urban areas and urban population result in various changes in the urban density (d) in the ten megalopolises. On the one hand, the urban density (d) in the YRD and the BTJ has decreased over the studied period, indicating an urban sprawl in the two megalopolises. Thus, the declining urban density (d) in the YRD and the BTJ offset 23.3 MtC (−11.6% of the total increase) and 13.3 MtC (−9.4%) emissions, respectively, from 1985 to 2010. On the other hand, the labor-intensive industry of the PRD, known as the factory of the world, has attracted millions in migration from 1985 to 2010 (NBSC 2001, 2011). The urban density (d) in the PRD continues to increase over the studied period, making the largest positive contribution (22.6 MtC, 23.1% of the changes in the PRD) to CO_2 emissions. Overall, the urban densities in the other seven megalopolises overall increase slightly, contributing 10.8 MtC (2.9% of the total increase) emissions from 1985 to 2010.

The intensity effect

A reduction in the energy intensity of GDP (e) and the related carbon intensity (c) is a major method of satisfying the emission reduction target. As shown in Fig. 5, overall, the reduction in energy intensity (e) overall offsets 86% of the increase in CO_2 (−116 MtC) from 1985 to 2000. The decoupling role of e, however, decreases slightly in the recent period (2000–2010), only offsetting the CO_2 emissions by 30 MtC (4% of the change) in Chinese megalopolises. This is even worse in some megalopolises, such as the QJM, the GZM, and the CZT megalopolises. The changes in energy intensity (e) in the three megalopolises add 31 MtC of emissions.

We further disaggregate the contributions of energy intensity (e) into the four sectors, to identify the individual intensity effect on the CO_2 emissions in the four sectors (Fig. 9). From 1985 to 2000, all of the four sectors, namely, the industry, construction, transportation, and service sectors, have a negative effect on the increasing CO_2 emissions, offsetting 116 MtC emissions, with the industry sector dominating the decreasing energy intensity. This situation changes from 2000 to 2010. The intensity in the QJM leads to an increase in CO_2 emissions, adding 26.6 MtC CO_2 emissions from 2000 to 2010. The contributions of the energy intensity in the construction sector in the PRD also substantially increased, adding 14.4 MtC emissions during the same period. However, the contributions of the energy intensity of the industry sector in the YRD however continually decreased, offsetting 22.8 MtC CO_2 emissions in the post-2000 period. It remains the largest decoupling sector across the ten megalopolises from 2000 to 2010. It is notable that the energy intensities of the transportation sector in all Chinese megalopolises, except the GZM, have a positive effect on the CO_2 emissions, adding 8.8 MtC emissions from 2000 to 2010, due to the rapid growth in private cars and the demand from the logistics industry.

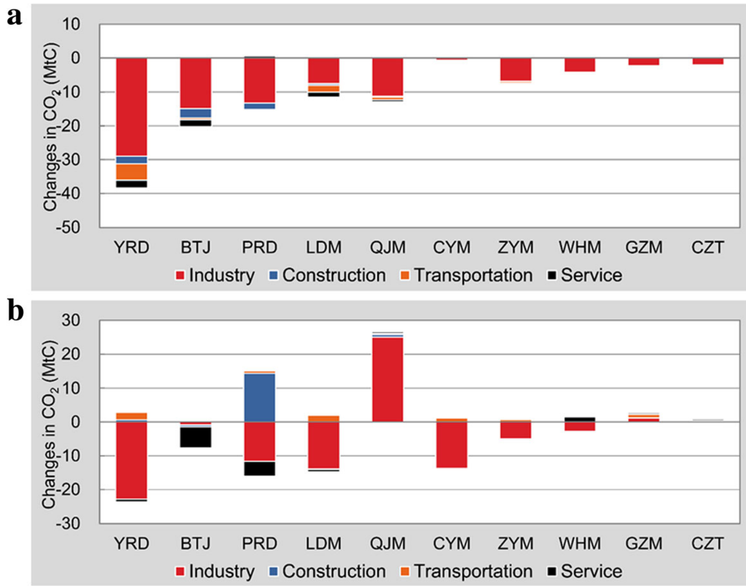


Fig. 9 The contributions of the changes in energy intensity to CO_2 emissions in the Chinese megalopolises. **a** Changes in CO_2 emissions from 1985 to 2000 and **b** changes in CO_2 emissions from 2000 to 2010. The full names of the ten megalopolises' codes are defined in Table 1. *Data source*: China City Statistical Yearbook and authors' calculation

In the industry sector, taking the *Nonmetal Mineral Products* (Industry Code 31) industry in the PRD as an example, the industry value added and the total energy consumption of it increased by 6.3 and 2.3 times from 2000 to 2010, respectively, resulting in a 62% decrease in the energy intensity since 2000. The most significant improvements in energy intensity occurred in the six energy-intensive industries, offsetting 30.1 MtC (−36% of the total increases) emissions from 2000 to 2010 (Fig. 8). It is also important to know that the share of the industry output of the four energy-intensive industries, increased throughout the same period. This finding is consistent with that of Shao et al. (2014), who find both an increase in the share of the industry output of the energy-intensive industries and a significant decrease in their energy intensities of them in Tianjin, China, from 1999 to 2010. The energy intensities of the remaining of 30 non-energy-intensive industries only reduced 22.6 MtC (−27% of the total increases) emissions during the same period. Therefore, to control the CO_2 emissions from the industry sector, the local governments should slow down the growth of energy-intensive industries and sufficiently promote the improvement of the energy intensity of these industries.

Compared to the large decoupling effect of energy intensity (e), the carbon intensity (f), plays a minor role in carbon reduction. Overall, it offsets 12 MtC throughout the studied period, with 100% occurring in the post-2000 period due to the relatively stable fuel mix of energy in China from 1985 to 2000. Induced by the huge energy demand in the YRD, the BTJ, and the PRD in the post-2000 period, the coal consumption, and therefore the share of coal in the total energy consumption increases, adding 8 MtC CO_2 emissions in the three megalopolises. The share of coal in the remaining seven megalopolises, decreased slightly, offsetting 20 MtC CO_2 emissions throughout the same period.

Discussions

Taking Chinese megalopolises as case study, the decomposition analysis indicates that booming economic growth (g) and urbanization (A) are the major contributors to the increasing CO_2 emissions in Chinese megalopolises, particularly in the post-2000 period. The decoupling effect of energy intensity (e) has reversed in some regions since 2000. The industry sector is the largest sector in adding CO_2 emissions due to its large economic scale. It is also the largest sector in decoupling CO_2 emissions due to its significant improvement in energy intensity. A sub-sector decomposition analysis of the industry sector in the PRD shows that the growth in output (G_j) of the six energy-intensive industries is the largest contributors to the increasing CO_2 from the industry sector. The share of the industry output (s_j) of the four energy-intensive industries, namely, *Petroleum Refining, Coking and Nuclear Fuel Processing* (Industry Code 25), *Manufacture of Raw Chemical Materials and Chemical Products* (Industry Code 26), *Smelting and Pressing of*

Ferrous Metals (Industry Code 32), and *Smelting and Pressing of Nonferrous Metals* (Industry Code 33), even increase during the examined period, making the industry sector dirtier. However, the improvements in the energy intensity (e_j) of the six energy-intensive industries have the most significant decoupling effects in the industry sector across the PRD. Other than the significant contributions of economic growth (g), expanding urban areas (A), and energy intensity (e), the other decomposition factors, namely, population density (d), economic structure (s), and carbon intensity (f) play a minor role in the increasing CO_2 emissions over the studied period. The findings are consistent with previous studies conducted at a city scale in China (Shao et al. 2014; Wang et al. 2014a; Yu et al. 2015). Moreover, our analysis pays particular attentions to the effect of urbanization on increasing CO_2 emissions at an urban scale, using urban areas (A) and urban density (d) as explanatory variables. The findings are consistent with those of Yuan et al. (2015), who use urban population as an explanatory variable and concluded that, at a provincial level, urbanization is the largest driver behind economic growth in China.

The continued booming effect of economic growth (g) on CO_2 emissions is difficult to avoid. Although that many cities in China are now entering into a "new normal" phase of economic growth, the economy itself is still expected to grow at a middle-high rate of approximately 7%, which is still a leading engine of economic growth globally (Xinhua Net 2014). On the one hand, due to the large economic aggregate, the annual growth rate of 7% still calls for large amount of energy, emitting more CO_2, and more than 70% of the economy promotes emissions that occur in urban areas. On the other hand, infrastructure construction, including transport infrastructure and energy infrastructure, is an endogenous requirement due to the regional inequality and huge energy demand, which actually makes the economic model not as green as expected. Moreover, the local governments still pursue short-term economic growth rather than long-term environmental sustainability because the economy is the primary indicator in assessing the performance of local government officials. This phenomenon is evident in the higher economic growth targets but looser environmental protection in the regional 12th FYP compared to the national 12th FYP (Greenpeace 2011).

Industry is the major contributor to the increasing CO_2 emissions in Chinese megalopolises in 25-year period. Although that the share of energy-intensive industries in the PRD has increased over the examined period, nationwide, the average growth rate of energy-intensive output has significantly fallen in China, for example, the average increased rates of steel and cement, respectively, are 19.8 and 12.2% from 2000 to 2010, but these value decrease to 6.3 and 5.7% from 2011 to 2013, respectively (NBSC 2015). Moreover, industry energy intensity has continued to decrease, with the overall drop of 64.3% indicating that the successful improvement in industry carbon reduction in Chinese megalopolises. Thus, it is foreseeable that the economic size of the energy-intensive industry sector will grow slowly and that the room for a downward adjustment of industry emissions will be larger.

Greater attention should be pain to the contribution of expanding urban areas (A), which is the second largest driver of the growth in CO_2 emissions. The expanding urban areas are not an isolated contributor but are associated with the increasing migration of people and extensive infrastructure construction. People migrate from rural to urban areas for employment, resulting in higher income, a welfare concentration within urban areas, increased accessibility to electrical appliances, and changes in lifestyle. All of these changes lead to higher household emissions compared to those in rural areas in developing countries (O'Neill et al. 2010). Moreover, it is predicted that nearly 100 million people will migrate from rural to urban areas from 2010 to 2015 (the State Council 2011). This rapid urbanization demands more infrastructures and buildings in urban areas, leading to a continued boom in construction. The emissions induced by the rapid urbanization therefore warrant more policy attentions.

Given the foreseeable booming economy (g) and expanding urban areas (A) in China in the coming decades, reductions in the energy intensity of GDP (e) and the carbon intensity of energy (f) seem to be crucial due to their role in achieving the reduction target and satisfying the energy demand caused by the booming economy. However, it is observed that the decoupling effect of energy intensity (e) has even reserved in some megalopolises during the post-2000 period. Taking the industry sector in the QJM as an example, the energy intensity of the megalopolis increases sharply in the post-2000 period, due to the heavy concentration of industrial activities within the QJM (NBSC 2011). This finding is also evidenced by the decomposition results of the industry sector in the PRD. Despite the degradation of the energy intensity of industry in the PRD, the concentration of the four energy-intensive industries, actually increase from 2000 to 2010, reaching 5.5MtC emissions. This result is consistent with that of Shao et al. (2014), who indicated that the positive contributions of energy intensity in individual year can be attributed to the significant growth in the energy intensity of the four energy-intensive industries in Tianjin, China, from 2001 to 2009. Given the significant contributions of energy-intensive industries, carbon reduction measures should primarily focus on improving the energy intensity of energy-intensive industries in Chinese megalopolises. However, Wang and Chen (2010) found that the technology barrier between developed and developing countries makes such improvements more difficult. Additionally, Liu et al. (2012a) show that this technology barrier among Chinese megalopolises is even significant for some energy-intensive industries, such as electricity generation and cement processing. Unless significant efforts can be made by the central governments to balance technological development, this trend will pose a new challenge to inland megalopolises in maintaining the rapid economic growth supported by heavy industry and meeting the mitigation targets set by the central government.

In addition, the reduction in energy intensity is not a guarantee of reduced total emissions due to the highly concentrated economy in urban areas. Therefore, more attentions should be focused on the development of clean energy, which shows a high potential to lower the emissions growth. China has made major efforts in non-fossil fuel energy in recent decades. In the China—U.S. Joint Announcement on Climate Change, which is released on 12th November 2014, China intends to increase its consumption of non-fossil fuel energy to approximately 20% by 2030. This effort is certainly positive in building greener cities in China.

There are large regional differences hidden in the gross trends. Although it highlights the important role of urbanization as a driver in accelerating CO_2 emissions in Chinese megalopolises, our analysis also provides evidence on the regional differences among the drivers. The economy increased rapidly in coastal megalopolises at the beginning of the economic reform, due to the policy priorities, foreign direct investment, and migration from rural coastal and inland regions. By contrast, the inland megalopolises start their economic engines in 2000, when the central government launched the Western Development Program (the State Council 2000). Promoted by this program, more infrastructure and energy-intensive industries have been constructed in western regions, resulting in both energy intensity and the total CO_2 emissions. Although the coastal megalopolises emit more CO_2 in the absolute terms, the inland megalopolises show higher growth rates in the post-2000 period, signaling convergence (Huang and Meng 2013). The regional differences in the emissions drivers warrant more detailed analyses to provide a reference for the development of accurate emissions scenarios.

In addition, despite the huge amount of CO_2 emitted from megalopolises, as main engines of economic growth and technological innovation, there are opportunities for local governments to address climate change. China is striving to build low-carbon cities (Baeumler et al. 2012). Five provinces and eight cities, piloted by National Development and Reform Commissions (NDRC) for the national low-carbon province and city development program, have formed low-carbon plans to promote a low-carbon economic structure and fuel mix, increase R&D for low-carbon industry, guide low-carbon urban transportation systems, etc. These pioneering attempts will certainly provide successful experiments for cities in developing countries to curb their emissions.

Conclusion

To better understand the patterns and driving factors of CO_2 emissions in urban China, and to help formulate mitigation policies for local governments, which face increasing pressure from national reduction targets and policies, this paper has performed a decomposition analysis to assess the contributing factors to CO_2 emissions in ten Chinese megalopolises. The results indicate that the booming economic growth (g) and expanding urban areas (A) are two main contributors to the increasing CO_2 emissions in urban China. The decline in energy intensity is the major method of slowing down the increasing rate of CO_2 emissions. However, the decoupling effects of energy intensity has ceased or even reversed in some megalopolises since 2000 due to the intensive growth in the industry output in these regions. The decoupling effects of economic structure adjustment only occurred in the YRD, the BJT, and the PRD, the three most developed megalopolises in China. The economic structure in the three megalopolises has shifted steadily from industry dominated to industry-service dominated over the studied period. The fuel mix of energy use does not make a significant contribution to emissions growth.

The uncertainty of this study arises through two major avenues: data reliability and methodological bias.

Overall, considering the inaccuracy and inconsistent statistical population data in China, the potential contribution of urbanization to the increasing CO_2 emissions may be larger than the results that we present here, whereas the effect of economic growth may be smaller, additionally, the roles of the energy intensity and carbon intensity of GDP in decoupling the emissions growth may not be as significant as we report in this study. The methodological bias is regarded as an acceptable limitation considering its ability to capture the dynamics of urban CO_2 emissions at an urban scale with limited data.

Given the foreseeable economic growth and urbanization in urban China, reductions in the energy intensity of GDP warrant much more policy attentions due to their crucial roles in carbon reduction and in satisfying the energy demand caused by continued economic growth and urbanization. However, this analysis also poses great challenges for local governments. Taking the industry sector in the PRD as an example, despite the decrease in the energy intensity of industries in the PRD, the concentration of the four energy-intensive industries actually increases from 2000 to 2010, reaching 5.5MtC emissions. Without exception, all the four industries produce materials for constructions. There is no doubt that China is in the process of rapid urbanization. It is foreseeable that the energy demand induced by construction materials for urban infrastructure will continue to grow. Thus, to achieve the reductions targets, the local government should focus on the improvements in the energy intensity of energy-intensive industries. Moreover, given that previous studies have proven the existence of a technology barrier among Chinese megalopolises, we suggested that clean energy warrants much more attention to fulfill the energy demand induced by economic growth and urbanization and to meet the carbon reduction target set by the central government.

Finally, the local governments should seriously address the different driving forces of CO_2 emissions among Chinese megalopolises, and their policies should be localized. To achieve the carbon reduction targets, greater emphasis should be placed on the optimization of urban growth, which would profoundly affect the infrastructure construction in urban China.

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Appendix A The validity of the downscale model

The majority of the validities of the downscale model have been fully discussed in our previous work (Meng et al. 2014). We also describe them briefly here for easy of reference.

The downscale model starts with the assumption that spatially, there is a linear relationship between the nighttime light intensity and energy consumption, and CO_2 emissions:

$$\hat{F}_{it} = \alpha^* NTL_{it} + \beta_p + \varepsilon_{it} \tag{A.1}$$

where F is the estimated CO_2 emissions from pixel i in year t, NTL is the digital number (light intensity) of nighttime light imagery, α is the coefficient of NTL, and β is the provincial fixed effect for capturing the differences in economic, geographical and cultural conditions between provinces, which may affect the intensity of nighttime lights, and ε is the error term. We then use the provincial aggregated NTL and the calculated CO_2 emissions, which are calculated by the provincial energy balance table, to verify the linear relationship between the nighttime light intensity and CO_2 emissions. The same method is also used for the energy consumption data.

Table 3 shows the estimated results for the panel regression of CO_2 emissions. In columns (1) to (4) of Table 3, both the total CO_2 emissions and the sectoral CO_2 emissions, are used as the dependent variable, and the sum of NTL is the independent variables. As expected, the coefficients of α are all positively significant. The R^2 of the four regressions are 0.58 (service sector) to 0.77 (transportation sector). That is, the linear model can significantly explain the majority of the CO_2 emissions. To further check the robustness of the linear relationship, four variables, namely, provincial GDP in 2000 constant prices (2000 \$), the rate of population urbanization (%), the industry share of the total GDP (%), and the length of roads (km), are used as the explained variables in Equation (A1). The results are reported in columns (5)–(8) of Table 3. Despite adding four other explained variables, the sign and the significance of α are constant. Meanwhile, the explained ability of the linear model is only slightly improved. That is, the assumption of a linear relationship between the nighttime light intensity and CO_2 emissions is valid.

Table 4 reports the estimated results for the panel regression of energy consumption, and the similar conclusions are presented. Thus, to simplify, we only use the NTL as the proxy variable, to downscale the calculated energy and CO_2 emissions, as well as the sectoral data, into the pixel scale.

Table 3 The estimated results for the panel regression between provincial CO_2 emissions and nighttime light intensity

	CO_2 emissions				CO_2 emissions			
		Industry	Transportation	Service		Industry	Transportation	Service
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
NTL	1.2343***	1.2878***	1.7673***	0.9083***	0.6673***	0.7187***	1.1437***	0.5591***
	(31.3)	(29.8)	(38.51)	(20.53)	(− 9.64)	(10.24)	(14.67)	(6.64)
GDP					0.0945**	0.1111**	0.03969	0.0283
					(1.76)	(2.07)	(0.66)	(0.44)
Urbanization					0.02911	0.0336	0.1036	0.0193
					(0.61)	(0.07)	(0.19)	(0.33)
Industry share					0.3608**	1.1044***	− 1.1415	0.1132
					(2.85)	(8.54)	(− 0.91)	(0.73)
Length of road					0.3005***	0.3122***	0.3533***	0.1621***
					(7.39)	(7.54)	(7.71)	(3.28)
Observation	464	464	464	464	464	464	464	464
R-sq	0.6930	0.6717	0.7736	0.5805	0.6931	0.6955	0.7915	0.5954

All the values are transformed into the log format to reduce the influence of outliers. The numbers in parentheses denote the corresponding t-statistics.

***significance at the 0.001 level; **significance at the 0.01 level

Table 4 The estimated results for the panel regression between the provincial energy consumption and nighttime light intensity

	Energy consumption				Energy consumption			
		Industry	Transportation	Service		Industry	Transportation	Service
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
NTL	1.3229***	1.3531***	1.7868***	0.9355***	0.7316***	0.7433***	1.1542***	0.5662***
	(35.34)	(29.44)	(38.52)	(21.52)	(12.06)	(10.07)	(14.71)	(7.07)
GDP					0.0757	0.0924	0.0323	0.0039
					(1.63)	(1.63)	(0.54)	(0.06)
Urbanization					0.1722	0.0192	0.0064	0.0240
					(0.41)	(0.38)	(0.12)	(0.43)
Industry share					0.5633***	1.1858***	0.1169	0.1561
					(5.06)	(8.71)	(0.419)	(1.06)
Length of road					0.3162***	0.3333***	0.3617***	0.2071***
					(8.87)	(7.68)	(7.85)	(4.04)
Observation	464	464	464	464	464	464	464	464
R-sq	0.7421	0.6664	0.7370	0.5163	0.7710	0.7176	0.7933	0.6081

Note: all the values are transformed into the log format to reduce the influence of outliers. The numbers in parentheses denote the corresponding t-statistics

***significance at the 0.001 level; **significance at the 0.01 level

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