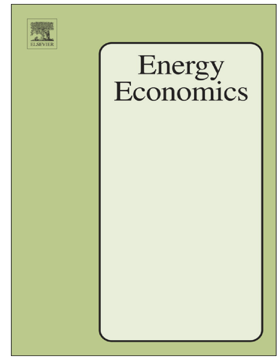
Accepted Manuscript



Regional development and carbon emissions in China

Jiali Zheng, Zhifu Mi, D'Maris Coffman, Stanimira Milcheva, Yuli Shan, Dabo Guan, Shouyang Wang

PII: S0140-9883(19)30082-9
DOI: https://doi.org/10.1016/j.eneco.2019.03.003
Reference: ENEECO 4330

To appear in: *Energy Economics*

Received date: 1 October 2018
Revised date: 7 January 2019
Accepted date: 4 March 2019

Please cite this article as: J. Zheng, Z. Mi, D. Coffman, et al., Regional development and carbon emissions in China, Energy Economics, https://doi.org/10.1016/j.eneco.2019.03.003

Regional development and carbon emissions in China

Jiali Zheng[abc], Zhifu Mi[a*], D'Maris Coffman[a], Stanimira Milcheva[a], Yuli Shan[d], Dabo Guan[d], Shouyang Wang[bc*]

[a] The Bartlett School of Construction and Project Management, University College London, London WC1E 7HB, UK

[b] Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing, 100190, China

[c] School of Economics and Management, University of Chinese Academy of Sciences, Beijing, 100190, China

[d] School of International Development, University of East Anglia, Norwich NR4 7TJ, UK

Abstract

China announced at the Paris Climate Change Conference in 2015 that the country would reach peak carbon emissions around 2030. Since then, widespread attention has been devoted to determining when and how this goal will be achieved. This study aims to explore the role of China's changing regional development patterns in the achievement of this goal. This study uses the logarithmic mean Divisia index (LMDI) to estimate seven socioeconomic drivers of the changes in CO_2 emissions in China since 2000. The results show that China's carbon emissions have plateaued since 2012 mainly because of energy efficiency gains and structural upgrading (i.e., industrial structure, energy mix and regional structure). Regional structure, measured by provincial economic growth shares, has drastically reduced CO_2 emissions since 2012. The effects of these drivers on emissions changes varied across regions due to their different regional development patterns. Industrial structure and energy mix resulted in emissions growth in some regions, but these two drivers led to emissions reduction at the national level. For example, industrial structure reduced China's CO_2 emissions by 1.0% from 2013-2016; however, it increased CO_2 emissions in the Northeast and Northwest regions by 1.7% and 0.9%, respectively. By studying China's plateauing CO_2 emissions in the new normal stage at the regional level, it is recommended that regions cooperate to improve development patterns.

Keywords: CO_2 emissions; LMDI; Regional development; Structural changes; New normal; China

***JEL* Classification:** O13; Q01; Q56; R15

*Corresponding authors: z.mi@ucl.ac.uk (Z. Mi), sywang@amss.ac.cn (S. Wang)

1 Introduction

Global warming is a worldwide environmental challenge that humanity faces. As the largest developing country and the largest carbon emitter in the world, China has made a series of solemn commitments to mitigate climate change. In particular, at the Paris Climate Change Conference held in November 2015, China announced that it will reach its carbon emission peak around 2030 and strive to achieve this peak before then (Liu, 2015). If the chosen path and implemented policies to reach that goal are appropriate, achieving this goal will not impose rigid constraints on China's economic or social development (Auffhammer and Carson, 2008). Instead, it will promote the transition of China's economic development pattern into green growth and low carbon (He, 2014). Therefore, in recent years, both the time span and the implementation path of carbon emission reductions in China have attracted widespread attention (Duan et al., 2018). A number of related studies reach the consensus that addressing carbon emission reductions at the regional level is crucial for China to achieve its goal in terms of policy (Chen and Groenewold, 2015), scenario (Mi et al., 2017c) and city (Shan et al., 2018a). China has actively participated in international climate governance to fight against climate change by top-down management, private voluntary actions and nongovernmental organizations (Liu et al., 2017).

Greenhouse gas (GHG) emissions, especially CO_2, and climate change caused by emissions are an environmental issue that is closely related to economic growth and social development (Moore et al., 2016). Dramatic changes in the structure of the Chinese economy in newly emerging sectors have had profound effects on the country’s overall CO_2 emissions. For example, China is rapidly catching up in the emerging photovoltaic industry with the production of new energy (Gao, 2012). Due to the slow-down in China’s economic growth (Green and Stern, 2017), CO_2 emissions in the country have plateaued since 2012 (Guan et al., 2018). It is important to promote models for sustainable development for China to achieve effective emission reductions under the goal of stable economic growth (Yu et al., 2018). As the Chinese government has already developed many low-carbon strategies and policies, economic development in China has entered a stage called the new normal. This new stage of development is characterized by a change from rapid growth and high-quantity development to high-quality development that is more inclusive and sustainable with structural improvements. The new development path will lead to higher per capita income and more energy-efficient buildings, smart transportation, service-based industries, etc. (Grubb et al., 2015). At present, a number of policies are being implemented to transform development patterns and to promote sustainable economic growth at both the national and regional levels, which will lead to cleaner production and lower carbon emissions (Shi and Xu, 2018).

Research on CO_2 emission reductions has yielded rich achievements and considerable progress. Related studies not only objectively evaluate historical contributions and different influences but also clarify the direction of and approaches to emission reductions in the future (Dietzenbacher et al., 2012). The drivers of emission changes at the national level include the population, the level of economic development, technology, the employment structure, the energy structure, the industrial structure, urbanization, industrialization, and openness, and most studies analyse the impact of multiple factors (Green and Stern, 2015; Mi et al., 2017a) . For example, the industrial structure change from heavy industry to the technology and service sectors has been identified as one of the main drivers of CO_2 emission reductions (Green and Stern, 2017; Mi et al., 2017a). Previous studies analyse factors from different perspectives based on time series models; however, most of them pay attention to the impact of economic structural changes on China's CO_2 emissions at the national level and ignore the differences in CO_2 emission changes across regions (Mi et al., 2017a). Whether at the international or domestic level, regional emissions are crucial to consider when discussing how to achieve emission reduction targets fairly and at the lowest cost (Rios and Gianmoena, 2018). In particular, the regional structure—measured by gross domestic product (GDP) shares of the territory, a measure formulated according to administrative and geographical criteria—has become an important factor driving the decline in CO_2 emissions in China in the new normal stage. In the future, it will also be necessary to further strengthen synergistic cooperation and mutual learning among regions (Dong et al., 2018).

This study discusses changes in China's CO_2 emissions caused by drivers in the context of economic structure and development patterns at the regional level. Research at the regional level has thus far focused on the transfer of emissions among regions and has failed to analyse the structural changes across regions in the new normal stage (Jiang et al., 2018). Previous studies have estimated carbon emission transfer across Chinese regions over time (Guo et al., 2012) and discussed the responsibilities of regions to reduce carbon emissions (Zhang, 2015). The relationship and interaction between interregional trade and regional emissions must also be considered (Hering and Poncet, 2014; Mi et al., 2017b). This paper closes this research gap by analysing China's regional CO_2 emission reductions from 2000 to 2016, which are attributed to structural changes and development patterns at the regional level.

Currently, most index decomposition analysis (IDA) processes neglect the direct and indirect effects of regional structure on emissions, and methods based on structural decomposition analysis (SDA) explain the influence of various factors only from the perspective of demand despite considering the interaction among regions. In addition, regions are crucial to mitigate carbon emissions in China because different provinces, with development differences, vary greatly in population, economy, and industry. However, studies on drivers at the regional level are limited. Thus, this paper fills the above research gaps by using logarithmic mean Divisia index (LMDI) decomposition analysis to clarify how various drivers affect CO_2 emissions at the regional level.

2 Methods and Data

2.1 LMDI

The methodology for analysing CO_2 emission drivers can be divided into two main categories. The first is based on decomposition analysis (DA), which measures how various factors contribute to emission reductions. The second is based on econometric methods that use panel data at the regional level (Zi et al., 2016). In contrast to DA, econometric models cannot decompose the contribution of each component to emission reductions; instead, they estimate the coefficient of the elasticity of each component in relation to emissions (Auffhammer and Carson, 2008).

DA methods have been widely used to quantify the contribution of socioeconomic drivers to environmental changes (Feng et al., 2015; Guan et al., 2008; Guan et al., 2009; Liu et al., 2016). At present, the two most popular decomposition methods are IDA (Ang, 2004; Chen and Yang, 2015) and SDA (Wang et al., 2009; Weber et al., 2008; Zhang and Tang, 2015). Based on input-output tables, SDA can distinguish indirect effects of changes among intermediate inputs and final demands, while IDA is extensively applied to time series analysis with section-detailed data (Hoekstra and Van den Bergh, 2003; Zhang et al., 2009). The classification of the IDA is obtained using the Laspeyres Index (Wang et al., 2005) and the Divisia Index (Dhakal et al., 2003). According to different weight-determining methods, the interpreted variable can be decomposed into the product of several factors, and the factor represents the increment of each index (Peters et al., 2017). The advantage of IDA is the relatively simple data and method, which can be easily applied at any level of aggregation (Ma and Stern, 2008).

According to existing research, among IDA methods, the LMDI is preferable for its path independence, aggregation consistency, and ability to handle zero values (Ang, 2005; Ang and Liu, 2001; Ang et al., 1998). For example, the LMDI can be used to analyse CO_2 emissions per capita by energy efficiency, energy consumption structure and energy intensity (Wu et al., 2005) as well as to study the effects of various factors on emissions (Li et al., 2015; Qi et al., 2016; Wang et al., 2016; Zhang et al., 2016). Consequently, LMDI is commonly used in studies to provide policy-relevant insights into, for example, the drivers of energy consumption (Ma and Stern, 2008; Zhang and Guo, 2013) and changes in CO_2 emissions (Jeong and Kim, 2013; Kang et al., 2014; Liu et al., 2007; Wang et al., 2013). LMDI analysis can be used to compare a series of indices and discuss their impact on emission trends during a given period from the base year to the reporting year (Ma and Stern, 2008).

In this study, the regional energy-related industrial CO_2 emissions in China (C^t) are decomposed as follows:

$$\begin{aligned} C^t &= \sum_i \sum_j \sum_k \frac{C_{ijk}}{E_{ijk}} \times \frac{E_{ijk}}{E_{jk}} \times \frac{E_{jk}}{E_k} \times \frac{E_k}{G_k} \times \frac{G_k}{G} \times \frac{G}{P} \times P \\ &= \sum_i \sum_j \sum_k c_{ijk} \times m_{ijk} \times s_{jk} \times e_k \times r_k \times g \times p \end{aligned} \tag{1}$$

where C_{ijk} is the CO_2 emissions of sector j by fuel type i in province k, representing regional energy-related industrial CO_2 emissions; E_{ijk} is the energy consumption of sector j by fuel type i in province k; G_k is GDP in province k; and P is the national population. Thus, based on Eq. (1), C^t is represented by seven factors, as follows:

1) $c = C_{ijk} / E_{ijk}$ is the emission intensity of fuel type i in sector j, reflecting the carbon content of coal, oil and gas;

2) $m = E_{ijk} / E_{jk}$ is the proportion of fuel type i in sector j and represents the energy mix effect, indicating the consumption of different fuel types;
3) $s = E_{jk} / E_k$ is sector j's share of the total energy inventory, representing the energy industrial structure;
4) $e = E_k / G_k$ is the energy intensity in province k and measures the energy consumption per unit of GDP, which indicates energy efficiency;
5) $r = G_k / G$ is province k's share of total GDP. The regional structure is defined as the organization or arrangement of a large geographical territory or a designated division of a country or state that may be formulated according to the economic criterion. Based on the definition of regional structure, regional growth measured by GDP, as an economic criterion, can be used to represent the divergence of regions (Fagerberg and Verspagen, 1996). By referring the measurement of regional production structure (Clark and Van Wincoop, 2001) and regional distance relation (Kalemli-Ozcan et al., 2003), GDP shares are used to represent the regional structure in this study;
6) $g = G / P$ stands for GDP per capita and measures economic growth; and
7) p is population.

Hence, the change in national CO_2 emissions (ΔC^t) in year t compared with year t-1 is calculated as

$$\begin{aligned}\Delta C^t &= \sum_i\sum_j\sum_k L\left(w_{ijk}^t, w_{ijk}^{t-1}\right)\ln\left(p^t/p^{t-1}\right) + \sum_i\sum_j\sum_k L\left(w_{ijk}^t, w_{ijk}^{t-1}\right)\ln\left(g^t/g^{t-1}\right) \\ &+ \sum_i\sum_j\sum_k L\left(w_{ijk}^t, w_{ijk}^{t-1}\right)\ln\left(r^t/r^{t-1}\right) + \sum_i\sum_j\sum_k L\left(w_{ijk}^t, w_{ijk}^{t-1}\right)\ln\left(e^t/e^{t-1}\right) \\ &+ \sum_i\sum_j\sum_k L\left(w_{ijk}^t, w_{ijk}^{t-1}\right)\ln\left(s^t/s^{t-1}\right) + \sum_i\sum_j\sum_k L\left(w_{ijk}^t, w_{ijk}^{t-1}\right)\ln\left(m^t/m^{t-1}\right) \\ &+ \sum_i\sum_j\sum_k L\left(w_{ijk}^t, w_{ijk}^{t-1}\right)\ln\left(c^t/c^{t-1}\right) \\ &= \Delta C_p + \Delta C_g + \Delta C_r + \Delta C_e + \Delta C_s + \Delta C_m + \Delta C_c\end{aligned} \tag{2}$$

where

$$L\left(w_{ijk}^t, w_{ijk}^{t-1}\right) = \left(C_{ijk}^t - C_{ijk}^{t-1}\right) \Big/ \left(\ln\left(C_{ijk}^t\right) - \ln\left(C_{ijk}^{t-1}\right)\right). \tag{3}$$

$L(w^t_{ijk}, w^{t-1}_{ijk})$, a weighting factor, is named the logarithmic mean weight. ΔC_p, ΔC_g ΔC_r, ΔC_e, ΔC_s, ΔC_m and ΔC_c are CO_2 emission changes caused by population variation, economic growth, regional structure adjustment, energy efficiency improvement, industrial structure upgrade, energy mix and emission intensity change, respectively.

2.2 Data Sources

This study uses two sets of data: the time series of regional CO_2 emissions and the corresponding energy consumption. There are two types of province sectoral CO_2 emissions: energy-related emissions (from fossil fuel combustion) and process-related emissions (from cement industry processes). The latter process-related emissions are calculated by the emission factor for the cement process, which is measured by CO_2 emitted in unit cement production as 0.2906 tonne CO_2 per tonne of cement (Liu et al., 2015). Emissions are calculated for 17 different energy types and 47 social economic sectors. Energy consumption data are obtained from China's National Energy Statistical Yearbook, while process-related data are obtained from China's Statistical Yearbook. Published by the National Bureau of Statistics of China (NBSC), China's GDP and population data can be derived from the National Statistics Yearbook.

Given the data availability, this study includes 30 provinces, excluding Tibet, Hong Kong, Macau and Taiwan. The 30 provinces are divided into eight Chinese regions (Feng et al., 2013; Mi et al., 2017b), including Beijing-Tianjin (i.e., Beijing and Tianjin), North (i.e., Hebei and Shandong), Northeast (i.e., Liaoning, Jilin and Heilongjiang), Central Coast (i.e., Shanghai, Jiangsu and Zhejiang), Central (i.e., Shanxi, Anhui, Jiangxi, Henan, Hubei and Hunan), South Coast (i.e., Fujian, Guangdong and Hainan), Southwest (i.e., Guangxi, Chongqing, Sichuan, Guizhou and Yunnan), and Northwest (i.e., Inner Mongolia, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang). The data have been checked in detail. The unit root test on CO_2 emissions shows that the sample data are stationary. Additionally, some missing data are addressed by inserting values under the assumption of the same annual emission growth rate: (1) Ningxia province sectoral CO_2 emissions and energy inventory in 2000, 2001 and 2002, (2) Hainan province sectoral CO_2 emissions and energy inventory in 2002, and (3) Shaanxi province energy inventory for the electric power, steam and hot water production and supply sector in 2011.

3 Results

3.1 Trends of CO_2 emissions in China

According to our estimations, CO_2 emissions in China from 2000-2016 grew significantly. Between 2000 and 2012, emissions grew at an average annual rate of 9.7%, from 2.9 Gt in 2000 to the high point of 8.9 Gt CO_2 in 2012 (Fig. 1A). Emissions then started to decline, bottoming out at 8.8 Gt in 2013, and they gradually plateaued, decreasing at an average annual rate of 0.2% from 2012 to 2016. In that four-year window, emissions peaked at 9.0 Gt CO_2 in 2015. CO_2 emissions in China during the 2000-2016 period can be divided into four 4-year stages: the WTO accession (2000-2004), high economic growth (2004-2008), post-financial crisis (2008-2012), and the new normal (2012-2016). Lacking officially published annual emissions data for China has led to great discrepancies in the current emissions estimated by academic institutes and scholars (Shan et al., 2018b), while the emission factor was used to adjust estimated emissions in this study.

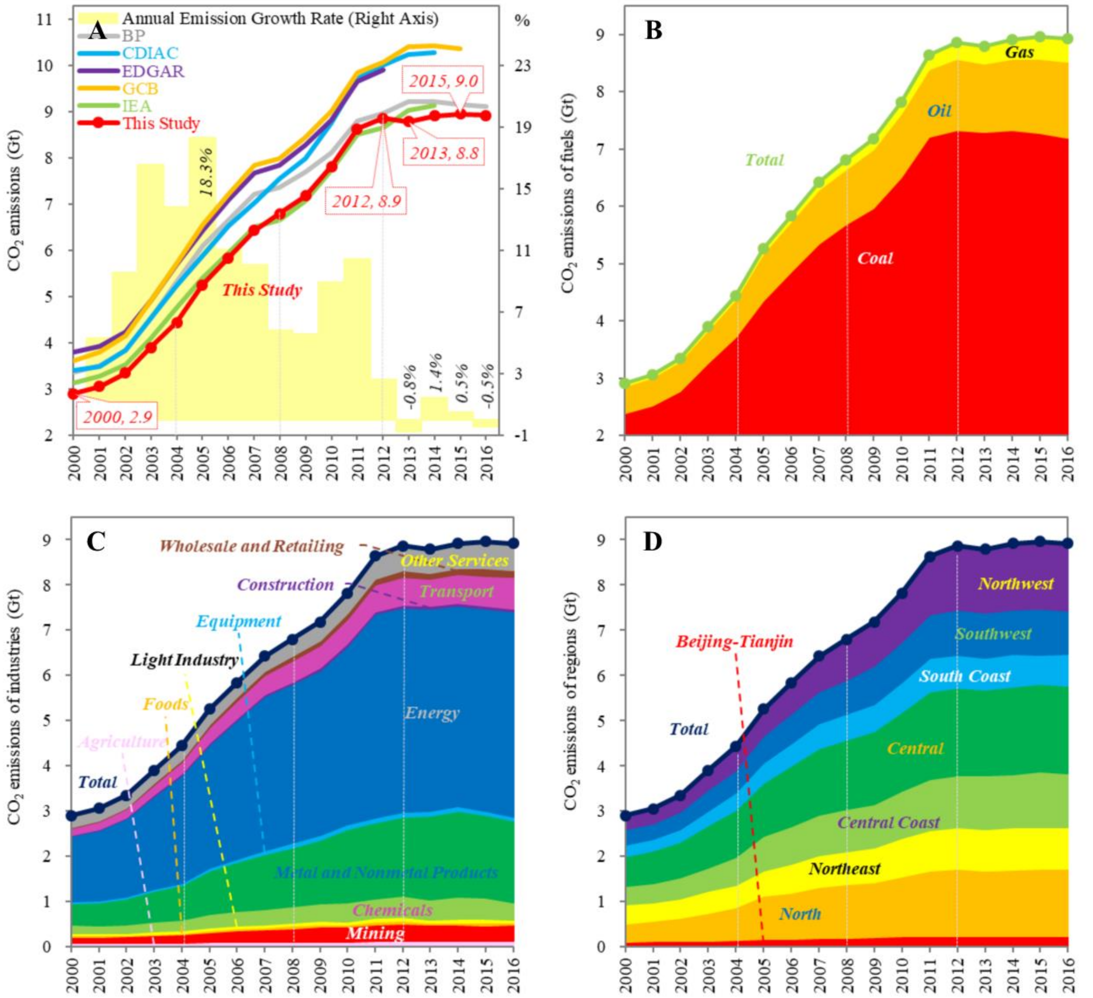


Fig. 1. Trends of CO_2 emissions in China. (A) Total CO_2 emissions in China from 2000-2016, according to different data sources: British Petroleum (BP) (BP, 2017), Carbon Dioxide Information Analysis Centre (CDIAC) (Boden et al., 2017), Emissions Database for Global Atmospheric Research (EDGAR) (Janssens-Maenhout et al., 2017), Global Carbon Budget (GCB) (Le Quéré et al., 2016) and International Energy Agency (IEA) (IEA, 2017); (B) total CO_2 emissions of three fuels (coal, oil, and gas) in China from 2000 to 2016; (C) total CO_2 emissions of twelve industries (agriculture, mining, foods, light industry, chemicals, metal and nonmetal products, equipment, energy, construction, transport, wholesale and retailing, and other services) in China from 2000 to 2016; (D) total CO_2 emissions of eight regions (Beijing-Tianjin, North, Northeast, Central Coast, Central, South Coast, Southwest, and Northwest) in China from 2000 to 2016.

The CO_2 emissions of different contributors were estimated, including three fuels (i.e., coal, oil, and gas), as shown in Table S1; twelve industries (i.e., agriculture, mining, foods, light industry, chemicals, metal and nonmetal products, equipment, energy, construction, transport, wholesale and retailing, and other services), as shown in Table S2; and eight regions (i.e., Beijing-Tianjin, North, Northeast, Central Coast, Central, South Coast, Southwest, and Northwest), as shown in Table S3. First, CO_2 emissions were well controlled by using clean energy rather than fossil fuel in the new normal stage. The share of coal-caused emissions decreased from 82.8% to 80.7%, but the share of gas-caused emissions increased from 3.3% to 4.4% (Fig. 1B). Additionally, with the upgrade of industrial structure, emissions gradually shifted from the secondary industry to the service industry. For example, the share of emissions in chemicals fell dramatically by 1.0%, while that of transport increased by 0.7% (Fig. 1C). In terms of regions, in the new normal stage, the Beijing-Tianjin (-0.2%), Northeast (-0.4%), Central (-0.1%), South Coast (-0.3%) and Southwest (-0.9%) regions showed declines in the share of emissions, whereas this share increased in the North (0.3%), Central Coast (0.5%) and Northwest (1.0%) regions (Fig. 1D).

3.2 Seven drivers of China's CO_2 emissions

Based on the LMDI, the contributions of seven socioeconomic factors to China's CO_2 emissions are analysed. These factors include population, economic growth, regional structure, energy efficiency, industrial structure, energy mix, and emission intensity. To facilitate presentation and discussion, results for 2000-2016 are subdivided from 2000-2016 into four 4-year stages, as mentioned above. The growth rate of China's CO_2 emissions in each 4-year stage fell from above 53% after the WTO accession but before the financial crisis (year 2008) to 30.3% after the financial crisis. Upon entering the new normal in 2012, it dropped sharply to 0.7% (Fig. 2).

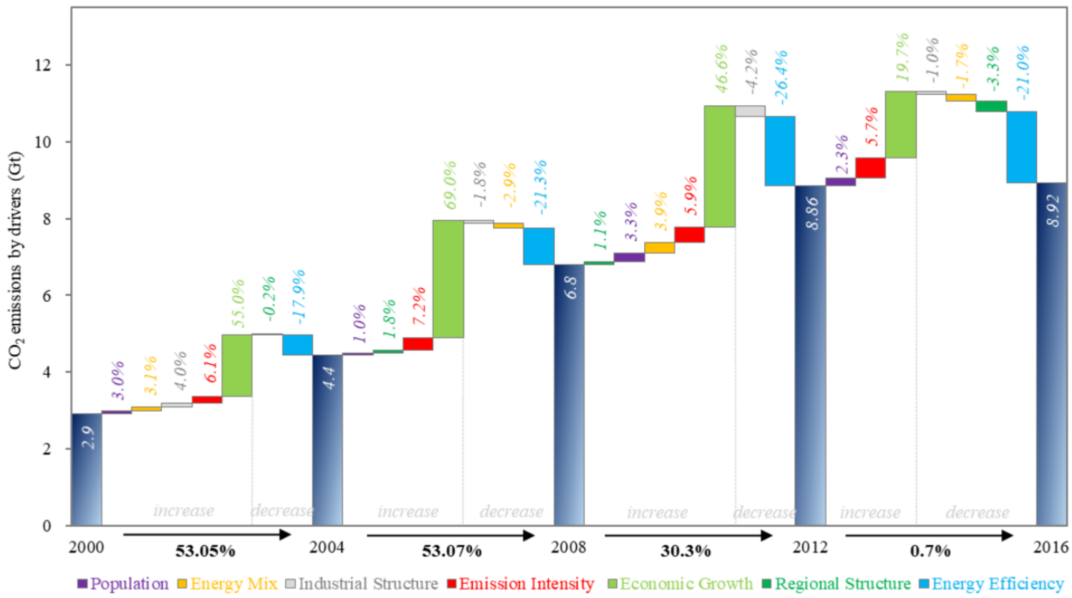


Fig. 2. Contributions of seven drivers to changes in national CO_2 emissions. The periods selected are 2000-2004, 2004-2008, 2008-2012 and 2012-2016, and the length of the bars reflects the contribution of each factor per stage.

Seven drivers of CO_2 emissions in China from 2001-2016 were assessed, when the slowing economic growth resulted in the deceleration in the emissions growth rate. The increase in China's CO_2 emissions was predominantly driven by rapid and monotonic economic growth that outpaced the growth of CO_2 emissions. However, this driver, falling from more than 40% every four years in the first three stages to 19.7% in the new normal stage, gradually led to a decrease in the emissions growth rate. China's economy, with a decelerating growth rate, is shifting from a high-quantity pattern with a rapid growth to a high-quality pattern with inclusive and sustainable improvements. Thus, economic restructuring has achieved the initial goals, and the effect of energy conservation and consumption reduction has become increasingly prominent, with more emphasis on quality and efficiency.

One of the important factors driving emission reductions during this period was the regional structural adjustment in China. This led to a change in emissions from positive values to negative values in the fourth stage, from an increase of 1.1% after the financial crisis to a decrease of 3.3% in the new normal stage. Hence, the optimization of the regional economic structure contributed immensely to emission reductions. Provinces in different regions have actively sought new economic growth points and strictly controlled high-polluting and high-energy-consuming projects for local economic development. Various growth points, including the emergence of the internet and finance, the rapid growth of e-commerce and logistics, the increase in information flows, and a growth driven more and more by consumption, have created a new impetus for development and become an important force in the economic transformation.

Additionally, energy efficiency improvements accounted for the greatest reductions in CO_2 emissions, at about -20% in each stage. The efficiency gains have benefited from the active promotion of advanced energy-saving and environment-protecting technologies. The industrial production structure has undergone positive changes with the elimination of backward production capacity, which has led to remarkable results and brought about obvious energy-saving effects. Therefore, energy consumption per unit of GDP is gradually declining. The substantial improvement of the technical level in the energy industry improves energy efficiency while creating social wealth.

Furthermore, the energy industrial structure continued reducing CO_2 emissions starting in the second stage, and it contributed -1.0% in the new normal stage. The growth rate of high-energy-consuming industries is slowing. Simultaneously, heavy industry, with high energy consumption, is decelerating, and the service industry, with relatively low energy consumption, continues to increase (Green and Stern, 2015; Mi et al., 2017b). Thus, the increasing proportion of tertiary industries, including service and high-tech industries, will alleviate the bottleneck in the shortage of energy resources, increase the efficiency of resource utilization, promote economic restructuring, and accelerate the transformation of economic development patterns.

Moreover, the energy mix contributed to emission reductions by -1.7% in the new normal stage. In the past 30 years, with rapid economic development, the production and consumption of high energy-consuming and high-polluting products have caused serious damage to the ecological environment. As a result, it is difficult to sustain previous energy supply and consumption patterns. To optimize the energy consumption structure, green and low-carbon strategy development has been proposed, including vigorously using non-fossil energy, actively developing hydropower, safely applying nuclear power, wind power and solar power, and solidly advancing geothermal and biomass energy (Guan et al., 2009; Mi et al., 2017a). Therefore, clean energy has become an important step in not only the energy structure adjustment but the entire economic restructuring. By further increasing the proportion of energy-saving and environmentally friendly clean energy consumption, continuously optimizing the energy consumption structure, and transforming the modes of energy development, the rapid growth of the new energy industry, with a series of policies, saves energy and reduces consumption.

Although population growth caused increases in emissions, the growth rate decreased to 2.3%. The emission intensity was almost stable, at about 6% throughout the entire period, with small fluctuations.

3.3 Emission changes caused by regional structure

China's CO_2 emissions have plateaued because the regional structure, measured by shares of regional economic growth, has changed. The regional structure represents one of the most significant factors in emission reductions. It went from increasing emissions by 1.1% in the post-financial crisis stage to decreasing emissions by -3.3% in the new normal stage. At the national level, population and economic growth, as two emission-increased factors, first caused an increase in emissions to 10.8 Gt in 2012, while regional structure then reduced carbon emissions by -3.3% for 2012-2016.

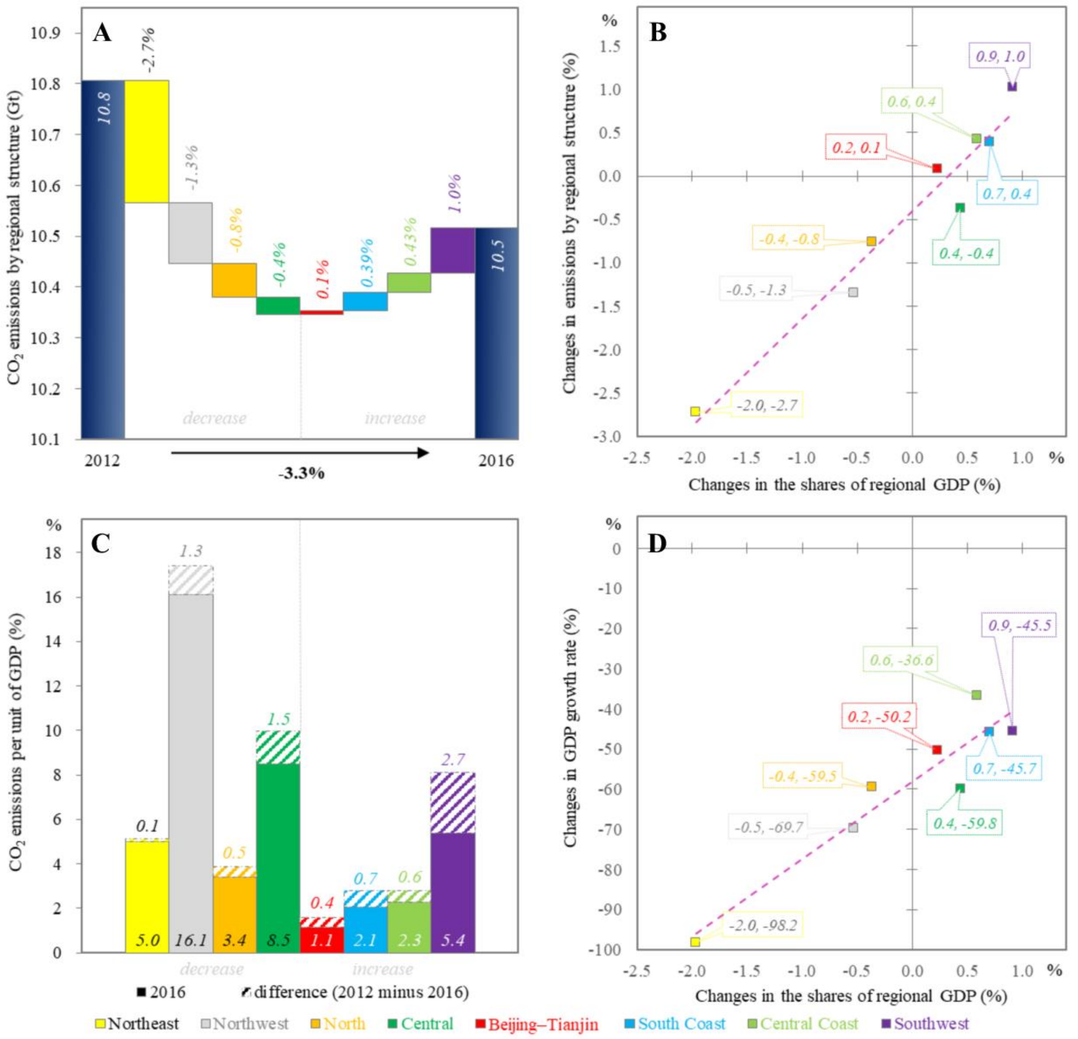


Fig. 3. Changes in CO_2 emissions caused by regional structure. (A) Region-specific contributions of regional structure to changes in national CO_2 emissions in the 2012-2016 period, with the length of the bars reflecting the contribution of each region in the last stage; (B) positive correlation between changes in emissions by regional structure and changes in the shares of regional GDP in the 2012-2016 period; (C) region-specific CO_2 emissions per unit of GDP in 2016 (the length of solid-filled bars) and the difference between 2012 and 2016 (the length of pattern-filled bars); (D) positive correlation between changes in GDP growth rate and changes in the shares of regional GDP in the 2012-2016 period.

In the absence of other drivers, the economic growth shares of eight regions contributed differently in terms of their regional structure (Fig. 3A). As the Northeast, Northwest, North and Central regions have relatively weak economic development and high energy-consuming emissions, regional structure adjustments in those regions have resulted in CO_2 emission reductions of -2.7%, -1.3%, -0.8% and -0.4%, respectively. All provinces in the Northeast and Northwest regions showed decreases in emissions, among which Liaoning in the Northeast contributed the largest reductions (-2.0%) nationwide. Therefore, the emissions caused by the regional structure in these two regions turned negative in the new normal stage after being positive in the post-financial crisis stage. However, emissions in the Beijing-Tianjin, South Coast, Central Coast and Southwest regions, which are relatively well developed, climbed slightly, by 0.1%, 0.39%, 0.43% and 1.0%, respectively. Among these areas, emissions in the two coastal regions, Central Coast and South Coast, grew sharply; this growth was driven by two rapidly developing provinces, Jiangsu and Guangdong, respectively. In the Southwest, the increased emissions were affected by the positive pulls of all provinces, with Guizhou accounting for 0.6%, ranking first in China.

The changes in emissions caused by regional structure were a result of changes in the shares of regional GDP because regional structure represents the relative contributions of different regions to national GDP. The linear trendline clearly showed a positive correlation between changes in emissions by regional structure and changes in the shares of regional GDP in the 2012-2016 stage (Fig. 3B). The increase in the share of regional GDP to national GDP accounted for the corresponding increase in emissions of the four well-developed regions mentioned above (Beijing-Tianjin, South Coast, Central Coast and Southwest) on the right side of the vertical axis; the more the share increased, the more the emissions increased. In contrast, the more the share decreased, the more the emissions decreased.

However, the above conclusions require regional CO_2 emissions per unit of GDP as a prerequisite. To reduce emissions by regional structure, the relative GDP shares of provinces with high CO_2 emissions per unit of GDP should decrease, while it might be better to increase the relative GDP shares of areas with low CO_2 emissions per unit of GDP. One reason is that the reduction in the share of regions with higher pollution and inefficient energy use would make the emission-reducing effect stronger. Another reason is that a partial decrease in regional shares requires a corresponding increase in the remaining shares due to the 100% overall national share; thus, it would be better to increase the shares of clean and efficient regions. To be exact, the CO_2 emissions per unit of GDP in 2016 in emission-reducing regions, including the Northeast (5.0), Northwest (16.1), North (3.4), and Central (8.5) regions, were higher than those of emission-increasing regions, including the Beijing-Tianjin (1.1), South Coast (2.1) and Central Coast (2.3) regions (Fig. 3C). Only the Southwest was an exception; this region's emissions increased, with high CO_2 emissions per unit of GDP of 5.4 in 2016. However, the difference of 2.7 between 2012 and 2016 was large. This shows that the relative value of CO_2 emissions per unit of GDP in the Southwest drastically decreased, although the absolute value was relatively high.

Going a step further, besides the above prerequisite, the conclusions about changes in the shares are explained by the fact that the regional GDP share changed because the regional GDP growth rate changed. The linear trendline clearly shows a positive correlation between changes in the regional economic growth rate and changes in the shares of regional GDP in the 2012-2016 stage (Fig. 3D). The slight decrease in the growth rate of regional GDP accounted for the corresponding increase in the regional GDP share of four emission-increasing regions on the right side of the vertical axis; the less the growth rate decreased, the more the share increased. In contrast, if the growth rate dramatically decreased, the share significantly decreased.

Table 1. Contributions of provinces in regional structure to CO_2 emission changes for 2012-2016

No. (*k*)	Provinces	Contributions	Regions
1	Beijing	*0.06%*	Beijing-Tianjin
2	Tianjin	*0.03%*	
3	Hebei	*-0.84%*	North
15	Shandong	*0.09%*	
6	Liaoning	*-2.04%*	Northeast
7	Jilin	*-0.21%*	
8	Heilongjiang	*-0.47%*	
9	Shanghai	*0.01%*	Central Coast
10	Jiangsu	*0.38%*	
11	Zhejiang	*0.04%*	
4	Shanxi	*-1.08%*	Central
12	Anhui	*0.19%*	
14	Jiangxi	*0.10%*	
16	Henan	*0.06%*	
17	Hubei	*0.24%*	
18	Hunan	*0.12%*	
13	Fujian	*0.18%*	South Coast
19	Guangdong	*0.19%*	
21	Hainan	*0.01%*	
20	Guangxi	*0.09%*	Southwest
22	Chongqing	*0.21%*	
23	Sichuan	*0.07%*	
24	Guizhou	*0.55%*	

25	Yunnan	*0.10%*	
5	InnerMongolia	*-1.03%*	Northwest
26	Shaanxi	*0.00%*	
27	Gansu	*-0.10%*	
28	Qinghai	*-0.01%*	
29	Ningxia	*0.00%*	
30	Xinjiang	*-0.21%*	

3.4 Regional emission changes by drivers

As regional development patterns have changed, China's CO_2 emissions have plateaued because of three region-level drivers: energy efficiency, industrial structure and energy mix.

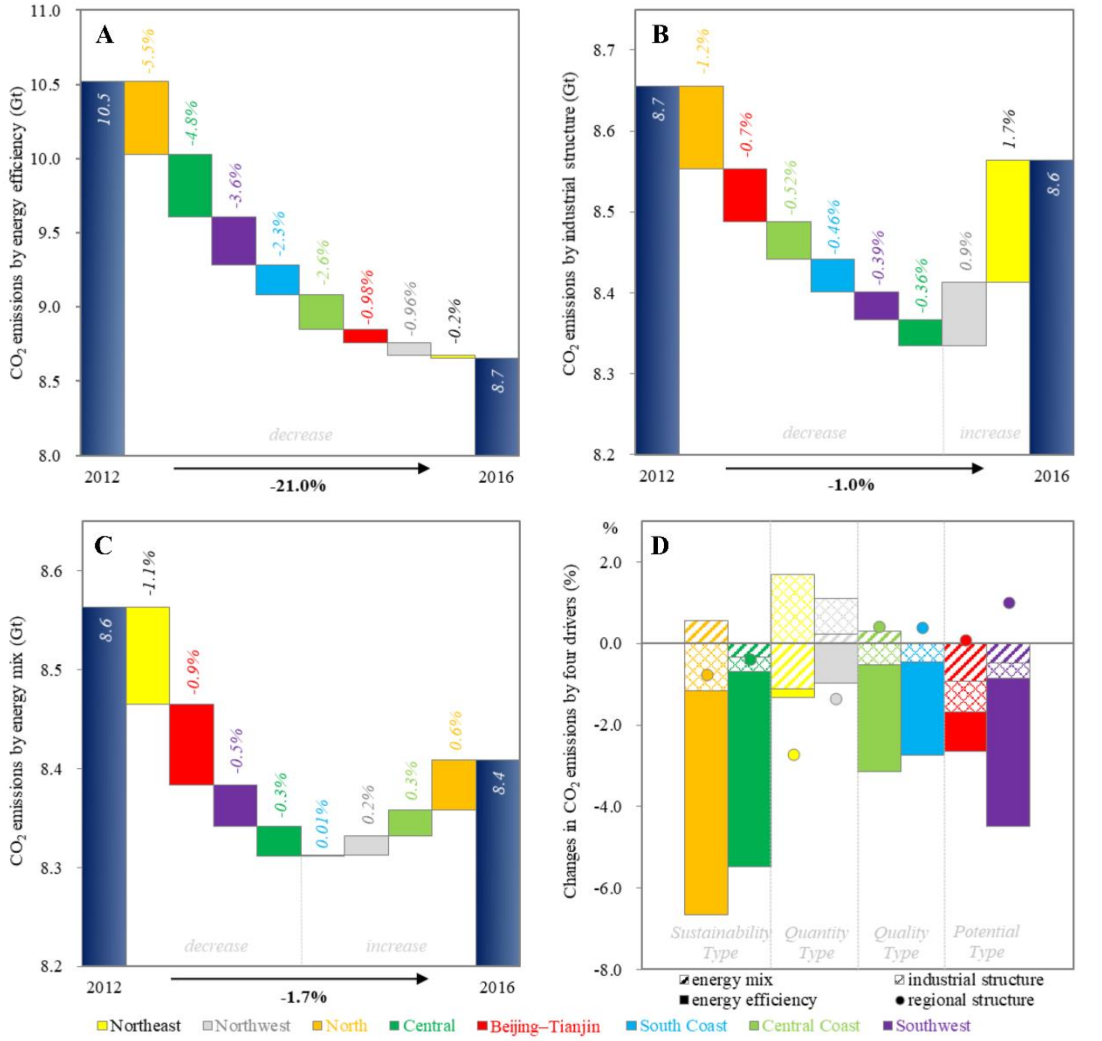


Fig. 4. Changes in CO_2 emissions caused by drivers at the regional level. (A) Region-specific contributions of energy efficiency to changes in national CO_2 emissions in the 2012-2016 period; (B) region-specific contributions of industrial structure to changes in national CO_2 emissions in the 2012-2016 period; (C) region-specific contributions of energy mix to changes in national CO_2 emissions in the 2012-2016 period; (D) regional comparison and classification of changes in CO_2 emissions driven by energy mix, industrial structure, energy efficiency and regional structure in

the 2012-2016 period, with the length of bars and markers reflecting the contribution of each region in the last stage.

Energy efficiency contributed the largest amount of emission reductions, at -21.0%, with no increases in emissions for all regions (Fig. 4A). The most prominent regions, in order, were the North, Central and Southwest regions. Two provinces in the North, Shandong and Hebei, contributed the largest amount of emission reductions, at -5.5%. These regions have become the top priorities in environmental protection governance, as they are major energy-consuming provinces adjacent to the capital city. Consequently, those two provinces implemented policies, including strict emission-limit standards, development of circular economy, etc., with considerably high administrative efficiency and steadily advanced the structure of de-capacity adjustment, which resulted in a significant increase in the efficiency of its unit energy use. By actively promoting innovation and improving quality through technologies, Shandong accounted for the largest emission reductions, at -4.6%. For example, energy corporations in Shandong actively responded to various policies to boost revenues for restructuring and upgrading. Similarly, Hebei promoted industrial green transformation and implemented efficiency-improving plans through “Internet Plus” and cloud computing. Thus, Hebei has achieved a gain in industrial energy efficiency and a decrease in emissions of -0.9%. More precisely, the full service and monitoring of energy management for key energy-using enterprises was implemented by building a network service information platform that included key enterprises in the province.

Second only to the North region, the Central region also contributed tremendous reductions of -4.8%. Hubei (-2.0%) and Henan (-1.4%) continued to upgrade their industrial layouts and structures with strategic support. Hubei has actively tried to use market-oriented measures through the carbon trading market to constrain enterprises and realize a low-carbon transition. As one of the first pilots of seven nationwide carbon emissions trading markets, Hubei promoted technological transformation, energy conservation and emission reduction. Henan also improved energy conservation and emission reduction mechanisms by establishing a sound supervision system to improve the visibility of project selection, reviews and publicity.

The third-ranked Southwest accounted for -3.6% in emission reductions. Five provinces in the Southwest contributed to these reductions, among which Guizhou was the greatest contributor at -1.0% in the new normal stage. Through the "double control" over energy consumption and intensity, Guizhou, as one of the first ecological civilization pilot areas in China, equally weighed the development and ecology. By strengthening key energy-saving and carbon-reducing projects, Guizhou has continuously explored new patterns for development, including low-carbon parks, communities and campuses based on technological innovation and resource recycling.

Compared with the reductions of the top three regions, emissions in the coastal regions declined less, with reductions of -2.6% in the Central Coast region and -2.3% in the South Coast region. In these regions, Jiangsu, Zhejiang and Guangdong, with high-quality economic and rapid development, performed well in energy consumption per unit because of their developed science and technology. Due to the relatively weak performance of Tianjin, the decrease in emissions in Beijing-Tianjin was only

-0.98%, but this figure was still slightly better than the -0.96% in the Northwest. The Northwest was crippled by Qinghai and Ningxia, though Shaanxi performed best among the six Northwest provinces. Therefore, the improvement caused by energy efficiency in the Northwest was unsatisfactory. Worse still, the Northeast, at -0.2%, struggled to rebound. Two of three provinces in the Northeast showed increases in emissions. Accumulated historical factors, including redundant state-owned enterprises, upgrading difficulties caused by geographical disadvantages, population loss and the economic downturn, led to few significant emission reductions caused by energy efficiency in the Northeast, which strongly relied on heavy industry.

CO_2 emissions in general were reduced (-1.0%) in the new normal stage due to the industrial structure, which varied by region (Fig. 4B). The North, Beijing-Tianjin, Central Coast, South Coast, Southwest and Central regions contributed different degrees of emission reductions (listed from the most to the least), but emissions increased in the Northeast and Northwest. Similar to energy efficiency, the two provinces in the North also contributed a maximum decrease (-1.2%) in emission reductions driven by industrial structure. Shandong still ranked first (-1.0%) in the nation. The overall large decline in Shandong was due to the decreasing trends in emissions caused by heavy industry represented by energy sector (-1.3%). The declining tendency after the financial crisis has accelerated, since the government has strictly controlled the growth of high-energy-consuming projects and industries by suspending approvals. Additionally, policies in Shandong focus on investing in energy-saving industries, accelerating emission-reducing projects and eliminating excess capacities.

In addition to the North region, the Beijing-Tianjin, Central Coast and South Coast regions, with a relatively developed economy and a high degree of openness, have played positive roles in reducing CO_2 emissions, accounting for -0.7%, -0.52% and -0.46%, respectively. Industrial structures continue to reduce emissions after the financial crisis until the new normal stage because of the rapid development of the tertiary industry in Beijing, the Yangtze River Delta and the Pearl River Delta, which represent the forefront of industrial transformation and upgrading.

Although the western and northern regions are not as open as the southeast, especially the coastal areas, the Southwest (-0.39%) has explored its own unique development path in recent years. Provinces in the Southwest are adjusting their structures through energy conservation breakthroughs that promote economic transformation and upgrades through the development of a green recycling economy, the elimination of backward production capacity and restrictions on high energy consumption projects. Tertiary industries, including big data and cloud computing in Guizhou, the tourism industry in Yunnan and Guangxi, and computer-related industries in Sichuan, are all of great significance for this region high-quality development. More specifically, Guizhou ranked second in the nation, contributing -0.6% to reductions. The adjustment of the energy consumption industrial structure has enabled Guizhou to shift its focus from high energy consumption to high-tech industries that have rapidly developed in recent years; for example, cloud computing is a typical representative in the nation. As a result, the increase in the proportion of tertiary industry services has led to a significant decrease in emissions. From the financial crisis to the new normal stage, Guizhou has successfully reduced emissions caused by heavy industry and light industry and vigorously developed high-tech industry.

Similarly, the Central region was strategically supported and reduced emissions (-0.36%). Despite the open strategy in the east and the Belt and Road policy in the west, provinces in the Central region still performed well. Although the development roads in Hunan, Hubei and Anhui in the Central region are still in the exploratory stage, these provinces are undertaking technological transfers from coastal areas and developing characteristic industry upgrades with a promising start. However, Shanxi increased emissions by 0.6%. Although Shanxi is the top priority for supply-side reforms such as de-capacity, removal without transformation cannot go beyond the fundamentals. The suspension of production forced by administrative policies can reduce absolute emissions only to a certain extent, but the output will decline accordingly, and it will not be possible to optimize the energy consumption structure and increase the relative efficiency of emissions. Hence, for historical reasons, emissions increased in energy sector (0.7%).

The situation in the Northwest, which is the focal point of development in the western region, was not optimistic. It accounted for an increase of 0.9%. Inner Mongolia (1.8%) ranked first in the country. Inner Mongolia's failure to actively seek transformation and upgrading as well as its relatively backward development are the main reasons for the poor performance of emission reductions, with energy sector increasing emissions by 1.9%. As the provinces in the Northwest have not explored the correct transformation and upgrading paths, they should learn from the experience of the Southwest to develop advantageous industries and achieve structural optimization. Even worse than in the Northwest, emission increases in the Northeast were as high as 1.7% for three provinces: Liaoning, Jilin and Heilongjiang. Problems with the industrial structure in the Northeast region have a long history. Since most companies in the Northeast are traditional state-owned enterprises, where corporate reforms were difficult to carry out, the economy lacks the vitality of the private economy. With a heavy industrial past, the secondary industry occupies an excessive proportion of the industrial structure. No measure has revitalized the economy, and the aging problem is serious. Hence, the effect of industrial structure on reductions in the Northeast is extremely poor.

Since various regions have accelerated the development of renewable energy, actively promoted the application of environmentally friendly materials, stimulated green consumption and built ecological civilizations, emissions have decreased (-1.7%) due to the energy mix (Fig. 4C). It is better to use relatively clean energies such as natural gas than to use fossil fuels such as coal or oil. Therefore, the emission reductions performance was good in the Southwest region (at -0.5%), where gas storage is abundant. The performance of the Central Coast (0.3%) and the South Coast (0.01%), at the end of the West-East Gas Pipeline, was relatively poor. Compared with the Southwest gas mines, the Northwest oil reserves are abundant, with a large number of high-yield oil fields. In addition, oil production in the

Northwest is still increasing, unlike the trend of exhaustion in the Northeast. Consequently, emissions caused by the energy mix in the Northwest increased by 0.2%. In contrast, the mining industry in the Northeast is facing slowing growth and shrinking outputs. Hence, CO_2 emissions caused by energy mix in the Northeast fell to -1.1%. Simultaneously, due to the influence of policies on pollution and the environment, emissions in Beijing-Tianjin (-0.9%) and the Central region (-0.3%) were controlled. Meanwhile, emissions in the North increased by 0.6% because of Hebei (0.5%), the worst performer.

In terms of drivers at the regional level, the eight regions can be divided into four types based on the reduction levels and driving effects: sustainability type (North and Central), quantity type (Northeast and Northwest), quality type (Central Coast and South Coast), and potential type (Beijing-Tianjin and Southwest) (Fig. 4D). The sustainability type, represented by the Central and North, provides a good example of decreases caused by regional structure, energy efficiency and industrial structure, from which efficient administrative policies can be learned to reduce emissions effectively. In addition, the gap in terms of the energy mix between the North and Central causes the emission reductions of the former to be lower than those of the latter, which can be offset by a greater use of clean energy. The quantity type, represented by the Northeast and the Northwest, mainly needs to strengthen and upgrade the industrial structure despite the satisfactory performance in the regional structure and energy efficiency. Similarly, the Northwest may follow the Northeast and optimize its energy mix by adjusting fuel types. The quality type, represented by the Central Coast and the South Coast, demonstrates that even with high economic growth, improving energy efficiency and upgrading the industrial structure can reduce emissions as a result of high-quality development. The potential type, represented by the Southwest and Beijing-Tianjin, varies in the final effect of emission reductions; however, driver changes in energy efficiency, industrial structure and energy mix leading to reductions are similar in this type of region, which reflects a promising future based on a proper start and an appropriate path.

4 Discussion

CO_2 emissions in China have plateaued, with a low growth rate of 0.7% from 2012-2016 (the new normal stage), due to changes in development patterns. Among the seven socioeconomic drivers decomposed by LMDI, emission intensity remained stable. Economic growth and population caused an increase in CO_2 emissions; however, a slow-down in the rates of economic growth and population growth decreased the growth rate of emissions. The remaining four drivers (i.e., regional structure, energy efficiency, industrial structure and energy mix) contributed to emission reductions at the national level in the new normal stage. In terms of regional structure, the optimizations of the regional GDP share made the regional structure lead to the second largest reduction in emissions. At the regional level, different regional development patterns resulted in different levels of changes in regional emissions caused by energy efficiency, industrial structure and energy mix.

The recent decline in emissions caused by shifts in China's economic structure and changes in regional development patterns was the result of sustainable strategies and low-carbon policies in the new normal stage. Improved energy efficiency and structural factors, including regional structure, industrial structure and energy mix, all resulted in emission reductions in this stage. First, all regions have coordinated and cooperated with each other to serve the major goal of restructuring the national economy from a high-speed pattern to a high-quality pattern. Second, the government has devoted more effort to improving energy efficiency; one example is the elimination of backward and outdated production capacity in energy-intensive industries in 2015. Third, central and local governments have issued preferential tax policies and investment dividends in the tertiary industry. Therefore, by improving the industrial structure, emissions in industries with high pollution and high energy consumption significantly declined, especially in heavy industry. Finally, policies, including the gradual decrease in investments in coal-fired plants, the wider use of electric vehicles, etc., have been implemented effectively. Consequently, the share of coal-caused emissions has continued to decrease based on upgrades in the energy structure and a greater use of clean energy, which is consistent with previous studies.

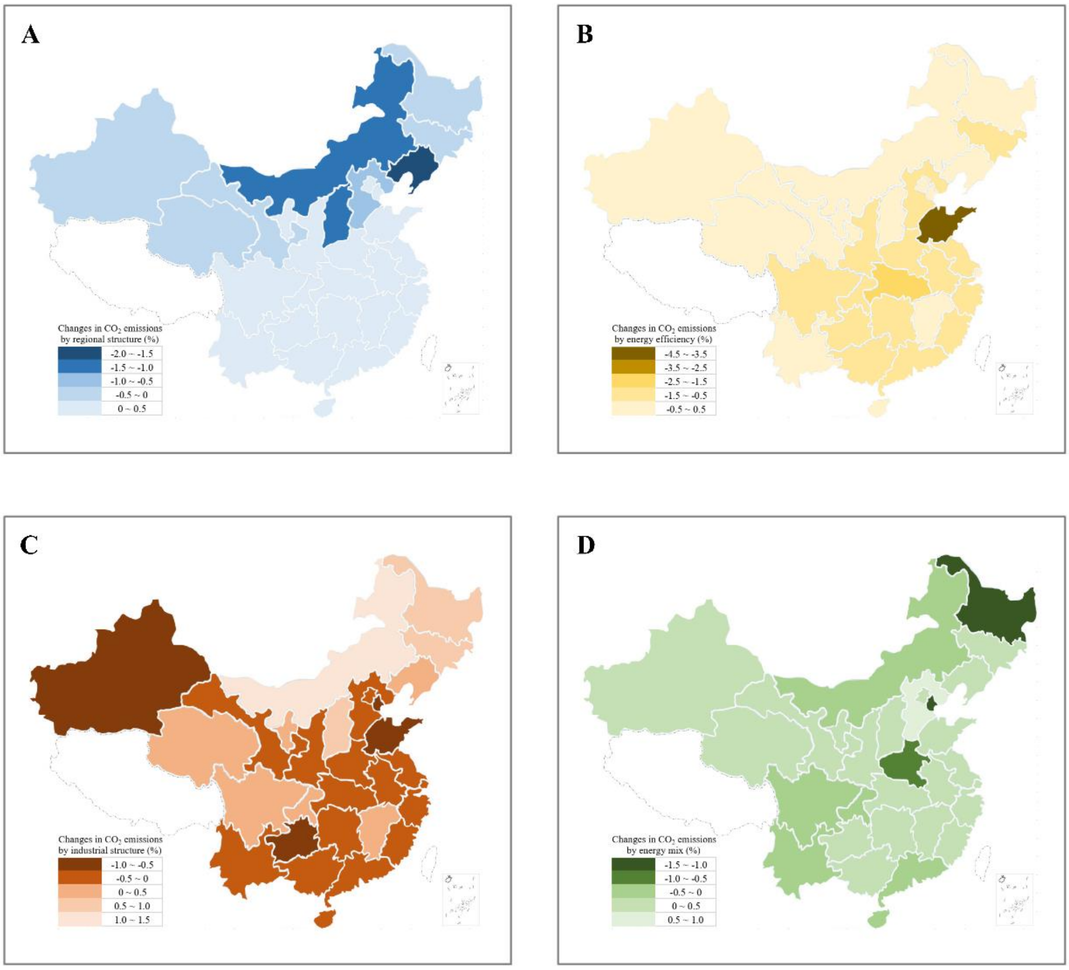


Fig. 5. Changes in regional CO_2 emissions caused by different drivers. (A) Changes in CO_2 emissions driven by regional structure in the 2012-2016 period; (B) changes in CO_2 emissions

driven by energy efficiency in the 2012-2016 period; (C) changes in CO_2 emissions driven by industrial structure in the 2012-2016 period; (D) changes in CO_2 emissions driven by energy mix in the 2012-2016 period. Shaded colours in maps indicate proportions of changes in emissions from 2012 to 2016.

Regional structure, represented by changes in regional GDP shares, has played an extremely important role in the emission reductions during the new normal stage (Fig. 5A). The structure in the new normal provides a good example to be continued, as emissions caused by share changes in the sustainability type (North and Central) and the quantity type (Northeast and Northwest) decreased, while the emissions and shares of the quality type (Central Coast and South Coast) and the potential type (Beijing-Tianjin and Southwest) increased. On the one hand, to reduce emissions by regional structure, the shares of provinces with lower energy efficiency and higher energy consumption should decrease, while the shares of areas with superior industrial and energy structures should increase. Hence, the optimization of the regional structure in GDP can reduce emissions. On the other hand, the rate of the decline in economic growth also affects the role of the regional structure in emissions because the slowing growth rate reduced the GDP share of the region. Compared with the post-financial crisis stage, regions with a decelerating growth rate in those four years of the new normal stage experienced a drop in total emissions. However, the corresponding growth rate declines of regions with slight increases in emissions caused by regional structure were relatively small. Consequently, it is necessary to control both the total amount and intensity of energy consumption based on GDP. In addition to introducing new projects to create new growth points for urban and provincial economic development, green development should be placed at the forefront of development, with energy consumption, structure, intensity and efficiency continuously improved.

The driving effects of energy efficiency, industrial structure and energy mix varied at the regional level because of different regional development patterns, which further led to the plateauing CO_2 emissions in the new normal stage. In particular, with emission reductions in all regions, energy efficiency contributed the most to emission reductions (Fig. 5B). The continuously improved industrial structure has resulted in emission reductions, while Northeast and Northwest increased their emissions because of poor transformation designs and a history of underdevelopment (Fig. 5C). The energy mix varied across regions but led to an overall decline in emissions, with a large decrease in resource-rich regions, especially in areas with abundant clean energy reserves. In contrast, eastern regions caused higher emissions (Fig. 5D). According to the regional differences in the factors described above, provinces should not blindly imitate others or change. Instead, the following two principles should be followed. First, poor-performing factors should be strengthened, while well-performing drivers should be maintained according to each region's own decomposition results. Second, it is more practical for regions to learn their advantages and strengths based on areas with situations similar to their own rather than simply embedding the experience from developed provinces. For example, efficient control of energy efficiency should be continued with regulations and policies under the administrative strategies in the North and Central regions, and it is better to continue with the advantages of transformation and upgrading in the Southwest. However, the reductions caused by energy efficiency in the Northwest and Northeast have been relatively weak. These regions, as industrial centres similar to the North and Central, can learn about their effective administrative measures. Additionally, the Northwest and Northeast are geographically disadvantaged areas similar to Southwest; thus, they can learn how the Southwest region designs its restructuring mechanisms by focusing on emerging industries with comparative advantages. Severe problems also exist in the industrial structure of the Northwest and Northeast. It may be difficult to imitate the high-speed and high-quality development of the tertiary industry in developed regions. It is therefore more practical for these regions to learn how to control heavy industry from the North and Central regions and to learn how to transfer knowledge from other industries to the high-tech industry in the Southwest. In terms of energy mix, the oppositely driven results of the North and Central, both classified as the sustainability type, can be adjusted by greater use of clean energy by the North. As above, characterized by the quantity type, the Northwest can follow the Northeast and optimize its energy mix by improving fuel types.

5 Conclusion

This study mainly analyses the causes of plateaued CO_2 emissions in China from 2012 to 2016 after a period of significant growth between 2000 and 2012. Based on the LMDI, the relative and absolute contributions of seven socioeconomic drivers to energy-related CO_2 emissions are decomposed. At the national level, population growth steadily increased emissions in China during the 2013-2016 period; however, there was a slow-down in the growth rate compared with the previous stages. In addition, the emission increases in China were dominated by strong economic growth, but the deceleration of this driver significantly accounted for the decline in the emission growth rate in the new normal stage. Most importantly, energy efficiency and structural changes resulted in a decline in CO_2 emissions in China in the new development stage.

At the regional level, China's carbon emissions have plateaued since 2012 mainly due to changes in the regional structure and development patterns. First, regional structure, estimated by regional GDP shares, drastically reduced carbon emissions in the new normal stage, whereas it used to be a cause of increased emissions. Second, due to changes in regional development patterns, the upgrading and improvement of energy efficiency, industrial structure and energy mix at the regional level led to CO_2 emission reductions in most regions. In this study, policy implications were discussed according to the results. CO_2 emissions varied by region due to different drivers; thus, corresponding countermeasures should be taken for different causes. Our analysis provides new insights into interregional cooperation, whereby regions can learn from the experiences of areas with similar situations but fewer emissions in order to improve their development patterns.

Acknowledgements
This study was supported by the National Key R&D Program of China (2016YFA0602604), the Natural Science Foundation of China (71761137001, 41629501), the UK Economic and Social Research Council (ES/L016028/1), Natural Environment Research Council (NE/N00714X/1) and British Academy Grant (AF150310).

References

Ang, B. W., 2004. Decomposition analysis for policymaking in energy: which is the preferred method? Energy policy 32, 1131-1139.

Ang, B. W., 2005. The LMDI approach to decomposition analysis: a practical guide. Energy policy 33, 867-871.

Ang, B. W., Liu, F. L., 2001. A new energy decomposition method: perfect in decomposition and consistent in aggregation. Energy 26, 537-548.

Ang, B. W., Zhang, F., Choi, K.-H., 1998. Factorizing changes in energy and environmental indicators through decomposition. Energy 23, 489-495.

Auffhammer, M., Carson, R. T., 2008. Forecasting the path of China's CO_2 emissions using province-level information. Journal of Environmental Economics and Management 55, 229-247.

Boden, T. A., Marland, G., Andres, R. J., 2017. Global, regional, and national fossil-fuel CO_2 emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, http://cdiac.ornl.gov/trends/emis/overview_2014.html.

BP, 2017. BP Statistical Review of World Energy 2017. British Petroleum (BP), London, https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

Chen, A., Groenewold, N., 2015. Emission reduction policy: A regional economic analysis for China. Economic Modelling 51, 136-152.

Chen, L., Yang, Z., 2015. A spatio-temporal decomposition analysis of energy-related CO_2 emission growth in China. Journal of Cleaner Production 103, 49-60.

Clark, T. E., Van Wincoop, E., 2001. Borders and business cycles. Journal of international Economics 55, 59-85.

Dhakal, S., Kaneko, S., Imura, H., 2003. CO_2 emissions from energy use in east Asian mega-cities: driving factors and their contributions. Environmental Systems Research 31, 209-216.

Dietzenbacher, E., Pei, J., Yang, C., 2012. Trade, production fragmentation, and China's carbon dioxide emissions. Journal of Environmental Economics and Management 64, 88-101.

Dong, K., Hochman, G., Zhang, Y., Sun, R., Li, H., Liao, H., 2018. CO_2 emissions, economic and population growth, and renewable energy: Empirical evidence across regions. Energy Economics 75, 180-192.

Duan, H., Mo, J., Fan, Y., Wang, S., 2018. Achieving China's energy and climate policy targets in 2030 under multiple uncertainties. Energy Economics 70, 45-60.

Fagerberg, J., Verspagen, B., 1996. Heading for divergence? Regional growth in Europe reconsidered. JCMS: Journal of Common Market Studies 34, 431-448.

Feng, K., Davis, S. J., Sun, L., Hubacek, K., 2015. Drivers of the US CO_2 emissions 1997-2013. Nature communications 6, 7714.

Feng, K., Davis, S. J., Sun, L., Li, X., Guan, D., Liu, W., Liu, Z., Hubacek, K., 2013. Outsourcing CO_2 within China. Proceedings of the National Academy of Sciences 110, 11654-11659.

Gao, Y., 2012. China as the workshop of the world: an analysis at the national and industrial level of China in the international division of labor. Routledge.

Green, F., Stern, N., 2015. China's "new normal": structural change, better growth, and peak emissions. Policy report, Centre for Climate Change Economics and Policy (CCCEP), University of Leeds.

Green, F., Stern, N., 2017. China's changing economy: implications for its carbon dioxide emissions. Climate policy 17, 423-442.

Grubb, M., Sha, F., Spencer, T., Hughes, N., Zhang, Z., Agnolucci, P., 2015. A review of Chinese CO_2 emission projections to 2030: the role of economic structure and policy. Climate Policy 15, S7-S39.

Guan, D., Hubacek, K., Weber, C. L., Peters, G. P., Reiner, D. M., 2008. The drivers of Chinese CO_2 emissions from 1980 to 2030. Global Environmental Change 18, 626-634.

Guan, D., Meng, J., Reiner, D. M., Zhang, N., Shan, Y., Mi, Z., Shao, S., Liu, Z., Zhang, Q., Davis, S. J., 2018. Structural decline in China's CO_2 emissions through transitions in industry and energy systems. Nature Geoscience 11, 551.

Guan, D., Peters, G. P., Weber, C. L., Hubacek, K., 2009. Journey to world top emitter: An analysis of the driving forces of China's recent CO_2 emissions surge. Geophysical Research Letters 36.

Guo, J. e., Zhang, Z., Meng, L., 2012. China's provincial CO_2 emissions embodied in international and interprovincial trade. Energy Policy 42, 486-497.

He, J.-K., 2014. An analysis of China's CO_2 emission peaking target and pathways. Advances in Climate Change Research 5, 155-161.

Hering, L., Poncet, S., 2014. Environmental policy and exports: Evidence from Chinese cities. Journal of Environmental Economics and Management 68, 296-318.

Hoekstra, R., Van den Bergh, J. C., 2003. Comparing structural decomposition analysis and index. Energy economics 25, 39-64.

IEA, 2017. CO_2 Emissions from Fuel Combustion 2017. International Energy Agency (IEA), Paris, France, http://www.iea.org/bookshop/757-CO752_Emissions_from_Fuel_Combustion_2017.

Janssens-Maenhout, G., Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Dentener, F., Bergamaschi, P., Pagliari, V., Olivier, J., Peters, J., 2017. EDGAR v4.3.2 Global Atlas of the three major Greenhouse Gas Emissions for the period 1970-2012. Earth Syst. Sci. Data Discuss, https://www.earth-syst-sci-data-discuss.net/essd-2017-2079/.

Jeong, K., Kim, S., 2013. LMDI decomposition analysis of greenhouse gas emissions in the Korean manufacturing sector. Energy Policy 62, 1245-1253.

Jiang, X., Guan, D., López, L. A., 2018. The global CO_2 emission cost of geographic shifts in international sourcing. Energy Economics 73, 122-134.

Kalemli-Ozcan, S., Sørensen, B. E., Yosha, O., 2003. Risk sharing and industrial specialization: Regional and international evidence. American Economic Review 93, 903-918.

Kang, J., Zhao, T., Liu, N., Zhang, X., Xu, X., Lin, T., 2014. A multi-sectoral decomposition analysis of city-level greenhouse gas emissions: case study of Tianjin, China. Energy 68, 562-571.

Le Quéré, C., Andrew, R. M., Canadell, J. G., Sitch, S., Korsbakken, J. I., Peters, G. P., Manning, A. C., Boden, T. A., Tans, P. P., Houghton, R. A., Keeling, R. F., Alin, S., Andrews, O. D., Anthoni, P., Barbero, L., Bopp, L., Chevallier, F., Chini, L. P., Ciais, P., Currie, K., Delire, C., Doney, S. C., Friedlingstein, P., Gkritzalis, T., Harris, I., Hauck, J., Haverd, V., Hoppema, M., Klein Goldewijk, K., Jain, A. K., Kato, E., Körtzinger, A., Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Lombardozzi, D., Melton, J. R., Metzl, N., Millero, F., Monteiro, P. M. S., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S.-I., O'Brien, K., Olsen, A., Omar, A. M., Ono, T., Pierrot, D., Poulter, B., Rödenbeck, C., Salisbury, J., Schuster, U., Schwinger, J., Séférian, R., Skjelvan, I., Stocker, B. D., Sutton, A. J., Takahashi, T., Tian, H., Tilbrook, B., van der Laan-Luijkx, I. T., van der Werf, G. R., Viovy, N., Walker, A. P., Wiltshire, A. J., Zaehle, S., 2016. Global Carbon Budget 2016. Earth Syst. Sci. Data, 8, 605-649, https://www.earth-syst-sci-data.net/8/605/2016/.

Li, W., Sun, S., Li, H., 2015. Decomposing the decoupling relationship between energy-related CO_2 emissions and economic growth in China. Natural Hazards 79, 977-997.

Liu, L., Wang, P., Wu, T., 2017. The role of nongovernmental organizations in China's climate change governance. Wiley Interdisciplinary Reviews: Climate Change 8, e483.

Liu, L. C., Fan, Y., Wu, G., Wei, Y. M., 2007. Using LMDI method to analyze the change of China's industrial CO_2 emissions from final fuel use: An empirical analysis. Energy Policy 35, 5892-5900.

Liu, Z., 2015. Steps to China's carbon peak. Nature 522, 279.

Liu, Z., Davis, S. J., Feng, K., Hubacek, K., Liang, S., Anadon, L. D., Chen, B., Liu, J., Yan, J., Guan, D., 2016. Targeted opportunities to address the climate-trade dilemma in China. Nature Climate Change 6, 201.

Liu, Z., Guan, D., Wei, W., Davis, S. J., Ciais, P., Bai, J., Peng, S., Zhang, Q., Hubacek, K., Marland, G., 2015. Reduced carbon emission estimates from fossil fuel combustion and cement production in China. Nature 524, 335.

Ma, C., Stern, D. I., 2008. China's changing energy intensity trend: a decomposition analysis. Energy economics 30, 1037-1053.

Mi, Z., Meng, J., Guan, D., Shan, Y., Liu, Z., Wang, Y., Feng, K., Wei, Y.-M., 2017a. Pattern changes in determinants of Chinese emissions. Environmental Research Letters 12, 074003.

Mi, Z., Meng, J., Guan, D., Shan, Y., Song, M., Wei, Y.-M., Liu, Z., Hubacek, K., 2017b. Chinese CO_2 emission flows have reversed since the global financial crisis. Nature communications 8, 1712.

Mi, Z., Wei, Y.-M., Wang, B., Meng, J., Liu, Z., Shan, Y., Liu, J., Guan, D., 2017c.

Socioeconomic impact assessment of China's CO_2 emissions peak prior to 2030. Journal of cleaner production 142, 2227-2236.

Moore, J. C., Chen, Y., Cui, X., Yuan, W., Dong, W., Gao, Y., Shi, P., 2016. Will China be the first to initiate climate engineering? Earth's Future 4, 588-595.

Peters, G. P., Andrew, R. M., Canadell, J. G., Fuss, S., Jackson, R. B., Korsbakken, J. I., Le Quéré, C., Nakicenovic, N., 2017. Key indicators to track current progress and future ambition of the Paris Agreement. Nature Climate Change 7, 118.

Qi, T., Weng, Y., Zhang, X., He, J., 2016. An analysis of the driving factors of energy-related CO_2 emission reduction in China from 2005 to 2013. Energy Economics 60, 15-22.

Rios, V., Gianmoena, L., 2018. Convergence in CO_2 emissions: A spatial economic analysis with cross-country interactions. Energy Economics 75, 222-238.

Shan, Y., Guan, D., Hubacek, K., Zheng, B., Davis, S. J., Jia, L., Liu, J., Liu, Z., Fromer, N., Mi, Z., 2018a. City-level climate change mitigation in China. Science advances 4, eaaq0390.

Shan, Y., Guan, D., Zheng, H., Ou, J., Li, Y., Meng, J., Mi, Z., Liu, Z., Zhang, Q., 2018b. China CO_2 emission accounts 1997-2015. Scientific data 5, 170201.

Shi, X., Xu, Z., 2018. Environmental regulation and firm exports: Evidence from the eleventh Five-Year Plan in China. Journal of Environmental Economics and Management 89, 187-200.

Wang, C., Chen, J., Zou, J., 2005. Decomposition of energy-related CO_2 emission in China: 1957-2000. Energy 30, 73-83.

Wang, J., Zhao, T., Xu, X., Zhang, X., 2016. Exploring the changes of energy-related carbon intensity in China: an extended Divisia index decomposition. Natural Hazards 83, 501-521.

Wang, K., Wang, C., Chen, J., 2009. Analysis of the economic impact of different Chinese climate policy options based on a CGE model incorporating endogenous technological change. Energy policy 37, 2930-2940.

Wang, Y., Zhu, Q., Geng, Y., 2013. Trajectory and driving factors for GHG emissions in the Chinese cement industry. Journal of Cleaner Production 53, 252-260.

Weber, C. L., Peters, G. P., Guan, D., Hubacek, K., 2008. The contribution of Chinese exports to climate change. Energy Policy 36, 3572-3577.

Wu, L., Kaneko, S., Matsuoka, S., 2005. Driving forces behind the stagnancy of China's energy-related CO_2 emissions from 1996 to 1999: the relative importance of structural change, intensity change and scale change. Energy policy 33, 319-335.

Yu, S., Zheng, S., Li, X., Li, L., 2018. China can peak its energy-related carbon emissions before 2025: Evidence from industry restructuring. Energy Economics 73, 91-107.

Zhang, M., Guo, F., 2013. Analysis of rural residential commercial energy consumption in China. Energy 52, 222-229.

Zhang, M., Mu, H., Ning, Y., Song, Y., 2009. Decomposition of energy-related CO_2 emission over 1991-2006 in China. Ecological Economics 68, 2122-2128.

Zhang, W., Li, K., Zhou, D., Zhang, W., Gao, H., 2016. Decomposition of intensity of energy-related CO_2 emission in Chinese provinces using the LMDI method. Energy Policy 92, 369-381.

Zhang, Y., 2015. Provincial responsibility for carbon emissions in China under different principles. Energy Policy 86, 142-153.

Zhang, Y., Tang, Z., 2015. Driving factors of carbon embodied in China's provincial exports. Energy Economics 51, 445-454.

Zi, C., Jie, W., Hong-Bo, C., 2016. CO_2 emissions and urbanization correlation in China based on threshold analysis. Ecological indicators 61, 193-201.

Highlights

We explore the role of China's changing regional development patterns in reducing carbon emissions.

Seven socioeconomic drivers of the changes in CO_2 emissions in China for 2000-2016 are estimated.

China’s carbon emissions have plateaued because of energy efficiency gains and structural upgrading.

The effects of these drivers on emissions changes varied across regions.

Regional structure has drastically reduced CO_2 emissions since 2012.

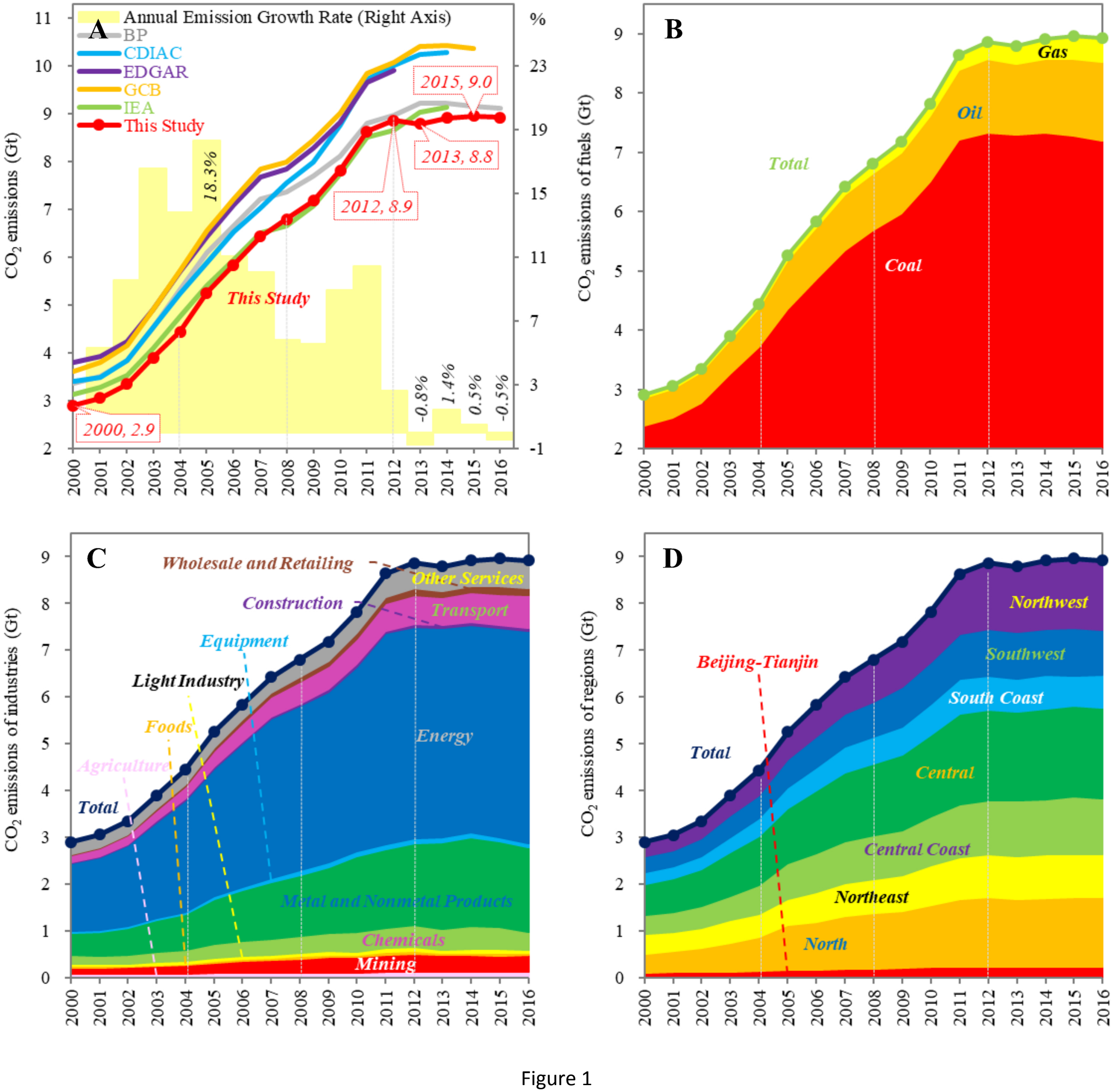
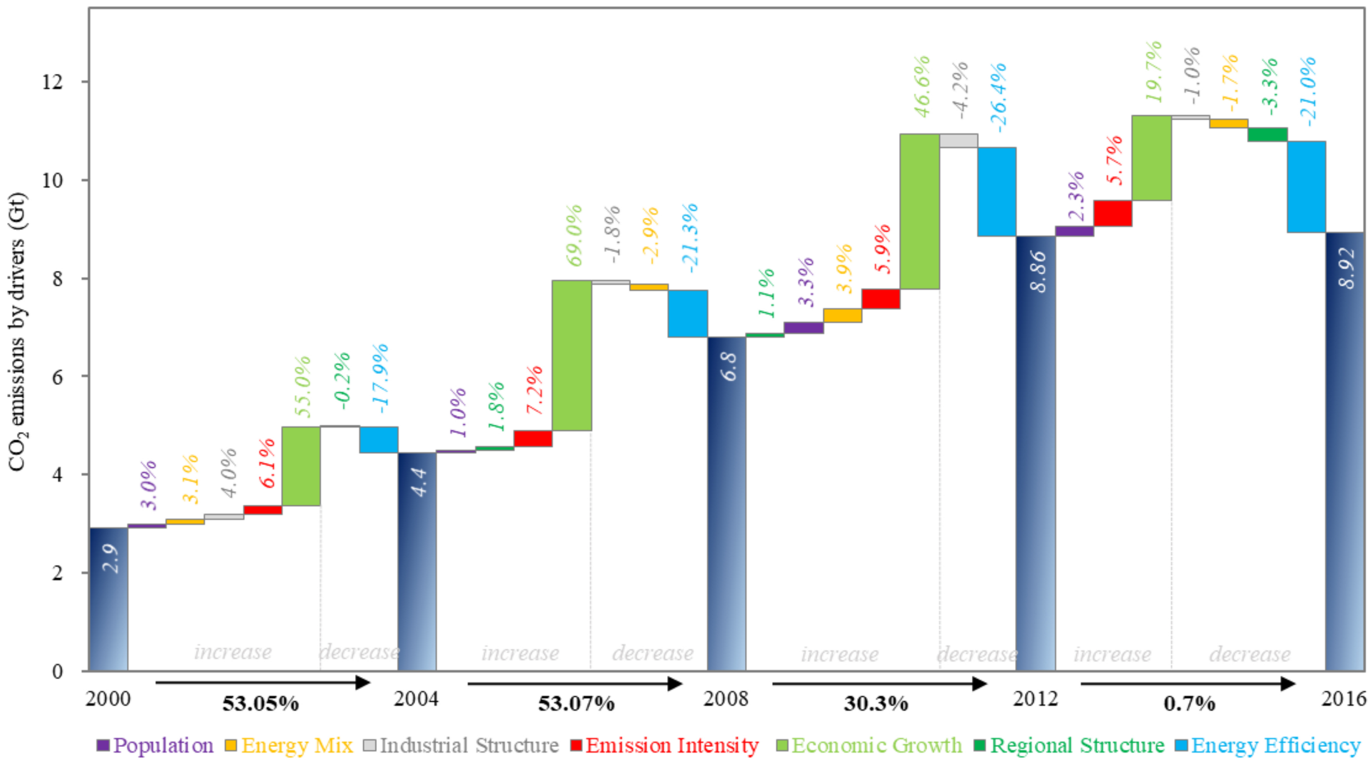
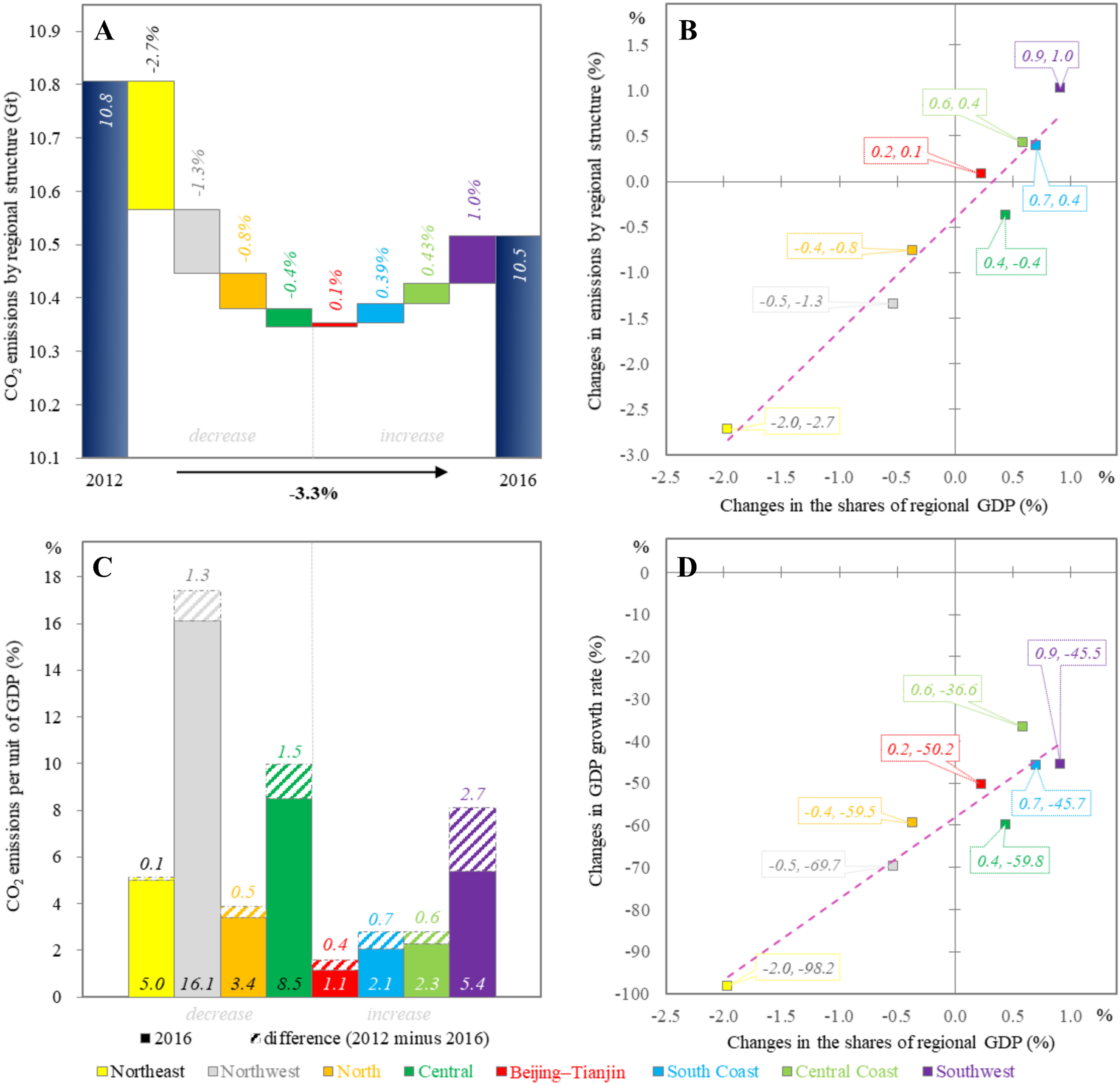

A
Annual Emission Growth Rate (Right Axis)
BP
CDIAC
EDGAR
GCB
IEA
This Study
2000, 2.9
2012, 8.9
2013, 8.8
2015, 9.0
18.3%
-0.8%
1.4%
0.5%
-0.5%
CO2 emissions (Gt)
%
B
Total
Coal
Oil
Gas
CO2 emissions of fuels (Gt)
C
Wholesale and Retailing
Other Services
Construction
Transport
Equipment
Light Industry
Foods
Agriculture
Total
Energy
Metal and Nonmetal Products
Chemicals
Mining
CO2 emissions of industries (Gt)
D
Northwest
Southwest
Beijing-Tianjin
South Coast
Total
Central
Central Coast
Northeast
North
CO2 emissions of regions (Gt)

Figure 1



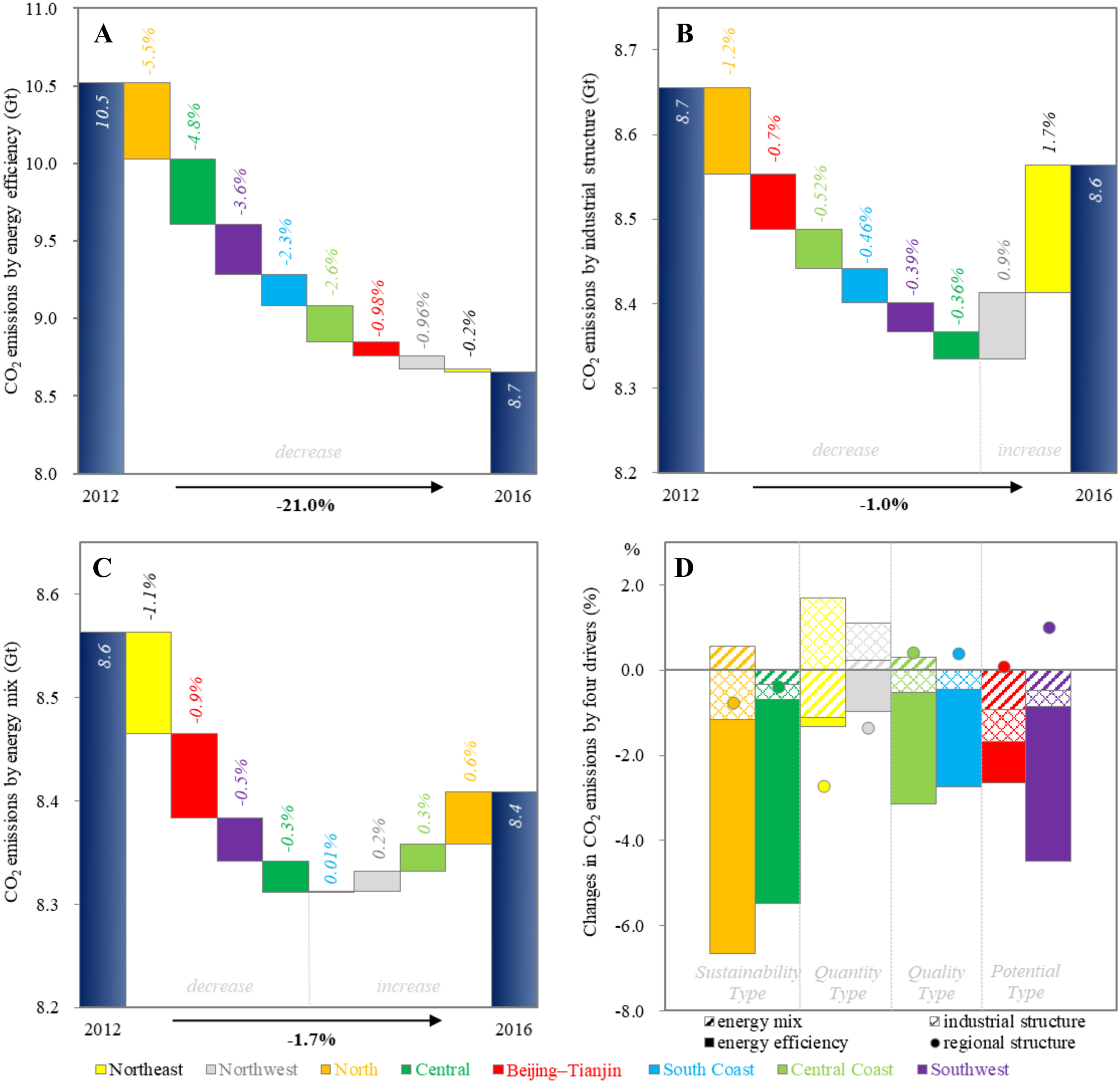
CO2 emissions by drivers (Gt)
0
2
4
6
8
10
12
2.9
3.0%
3.1%
4.0%
6.1%
55.0%
-0.2%
-17.9%
4.4
1.0%
1.8%
7.2%
69.0%
-1.8%
-2.9%
-21.3%
6.8
1.1%
3.3%
3.9%
5.9%
46.6%
-4.2%
-26.4%
8.86
2.3%
5.7%
19.7%
-1.0%
-1.7%
-3.3%
-21.0%
8.92
increase
decrease
increase
decrease
increase
decrease
increase
decrease
2000
53.05%
2004
53.07%
2008
30.3%
2012
0.7%
2016
Population
Energy Mix
Industrial Structure
Emission Intensity
Economic Growth
Regional Structure
Energy Efficiency

Figure 2



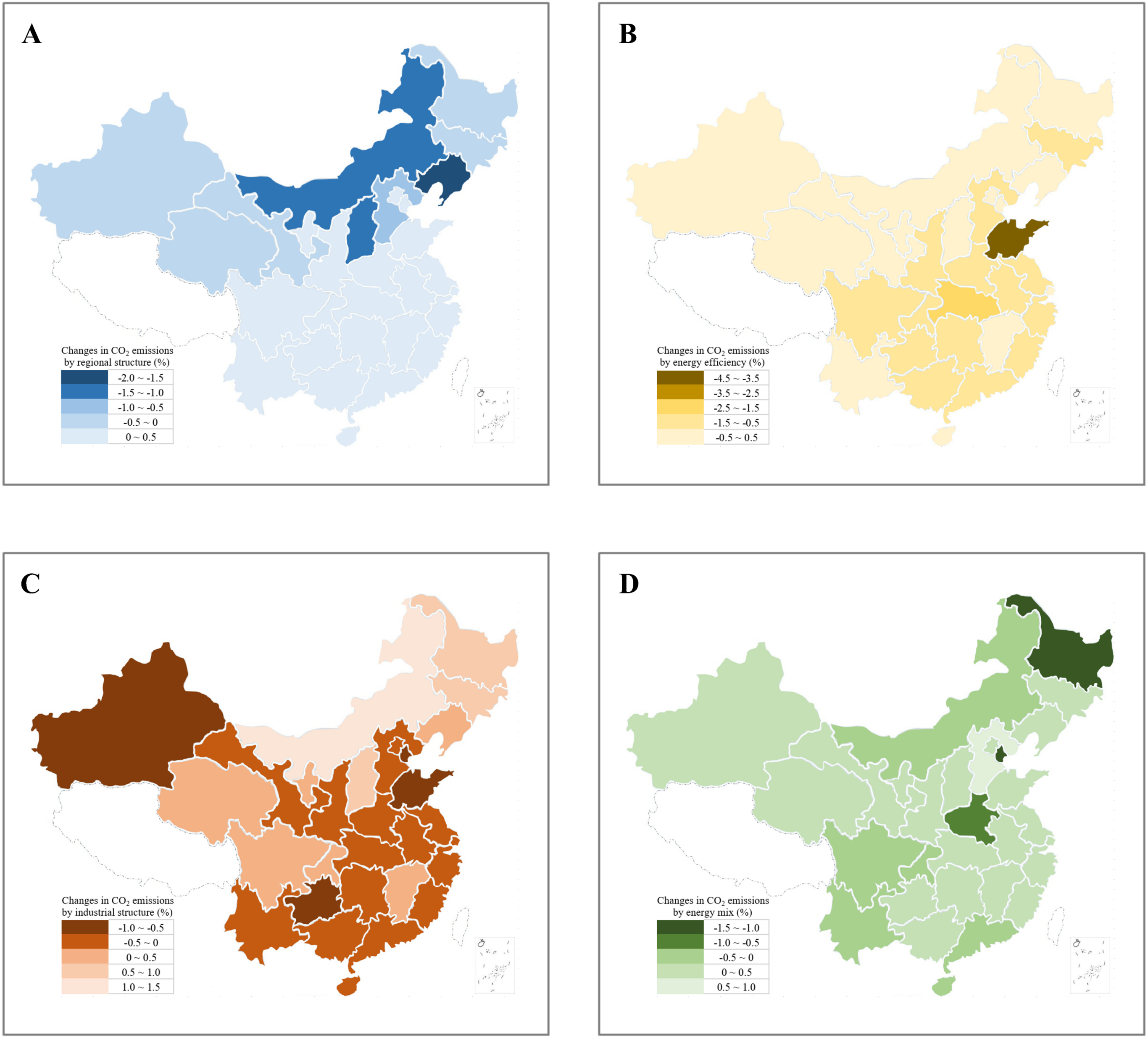
A
10.9
10.8
10.7
10.6
10.5
10.4
10.3
10.2
10.1
CO2 emissions by regional structure (Gt)
10.8
-2.7%
-1.3%
-0.8%
-0.4%
0.1%
0.39%
0.43%
1.0%
10.5
decrease
increase
2012
-3.3%
2016
B
%
Changes in emissions by regional structure (%)
Changes in the shares of regional GDP (%)
0.9, 1.0
0.6, 0.4
0.2, 0.1
0.7, 0.4
-0.4, -0.8
0.4, -0.4
-0.5, -1.3
-2.0, -2.7
C
%
CO2 emissions per unit of GDP (%)
1.3
0.1
0.5
1.5
0.4
0.7
0.6
2.7
5.0
16.1
3.4
8.5
1.1
2.1
2.3
5.4
decrease
increase
2016
difference (2012 minus 2016)
D
%
Changes in GDP growth rate (%)
Changes in the shares of regional GDP (%)
0.9, -45.5
0.6, -36.6
0.2, -50.2
0.7, -45.7
-0.4, -59.5
0.4, -59.8
-0.5, -69.7
-2.0, -98.2
Northeast
Northwest
North
Central
Beijing–Tianjin
South Coast
Central Coast
Southwest

Figure 3



A
B
C
D
CO2 emissions by energy efficiency (Gt)
CO2 emissions by industrial structure (Gt)
CO2 emissions by energy mix (Gt)
Changes in CO2 emissions by four drivers (%)
decrease
increase
2012
2016
-21.0%
-1.0%
-1.7%
Sustainability Type
Quantity Type
Quality Type
Potential Type
energy mix
industrial structure
energy efficiency
regional structure
Northeast
Northwest
North
Central
Beijing–Tianjin
South Coast
Central Coast
Southwest

Figure 4



A
Changes in CO_2 emissions by regional structure (%)
-2.0 ~ -1.5
-1.5 ~ -1.0
-1.0 ~ -0.5
-0.5 ~ 0
0 ~ 0.5
B
Changes in CO_2 emissions by energy efficiency (%)
-4.5 ~ -3.5
-3.5 ~ -2.5
-2.5 ~ -1.5
-1.5 ~ -0.5
-0.5 ~ 0.5
C
Changes in CO_2 emissions by industrial structure (%)
-1.0 ~ -0.5
-0.5 ~ 0
0 ~ 0.5
0.5 ~ 1.0
1.0 ~ 1.5
D
Changes in CO_2 emissions by energy mix (%)
-1.5 ~ -1.0
-1.0 ~ -0.5
-0.5 ~ 0
0 ~ 0.5
0.5 ~ 1.0

Figure 5