Master's Thesis

Urbanization's impacts on changes in CO_2 emissions in 30 provinces in China

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February, 2020

Abstract:

China's extensive and growing CO_2 emissions are linked to rapid economic development and advancing urbanization, posing serious concerns in the context of climate change. Decomposition analysis has been widely performed to identify drivers of China's CO_2 emissions. However, to date, no studies have examined the impacts of urbanization on CO_2 emissions across all of its provinces. Using provincial statistical data and six key factors influencing CO_2 emissions (carbon and energy intensity, residential consumption and consumption inhibition, and population urbanization and size), we applied the logarithmic mean Divisia index (LMDI) decomposition method to examine how urbanization affected CO_2 emission changes across 30 provinces between 1990 and 2016. Our results indicated that while urbanization's impacts on CO_2 emissions increased in China as a whole during this period, they were regionally differentiated. The energy intensity effect was the main driver of reduced CO_2 emissions, with carbon intensity exerting weaker effects in the 30 provinces, differentiated by their energy structures. The residential consumption effect, which is strongly linked to advancing urbanization, was the primary driver of increased CO_2 emissions in all of the provinces. While the consumption inhibition and population urbanization effects were positive at the national level, they were negative in highly urbanized provinces and in highly industrial provinces. These findings highlight the need to promote environmentally friendly consumption and to design regionally differentiated policies and optimized energy structures tailored to particular urbanization contexts. Moreover, they can provide valuable inputs for other developing countries undergoing continuous urbanization, contributing to efforts to balance economic development and environmental sustainability.

Keywords: Carbon dioxide emissions, decomposition, China, provincial-level analysis, urbanization, residential consumption

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1. Introduction

1.1 Background

Urbanization is not only the outcome but also a cause of economic development [1]. Economic globalization has contributed to the rapid development and accelerated urbanization of countries worldwide. Up to 2017, 54% of the world's population resided in urban areas and this proportion is expected to increase in the future [2]. The projected number of city dwellers will rise to 6 billion by 2045, reflecting an increase of 2 billion urban inhabitants compared with current numbers [3]. Following China's implementation of its reform and opening-up policy, its gross domestic product (GDP) increased almost 200 times from 367.87 billion yuan in 1978 to 74.11 trillion yuan in 2016. During the same period, China's urban population increased from 172.45 to 792.98 million [4]. In addition, the country's urbanization rate rose from 17.9% to 58.5%, reflecting an average annual increase rate of nearly one percentage point. However, given an average urbanization rate of 72.6% for developed countries, there is further scope for urbanization in China in the future [5].

Advancing urbanization leads to an increase in CO_2 emissions. Moreover, studies have found that the growth rate of the increment in CO_2 emissions is positively associated with the speed of urbanization [6]. For example, Wang et al. [7] showed that energy use increased markedly with urbanization, resulting in the production of greater quantities of CO_2 emissions. In developing countries, urbanization is a key source of regional economic development, and its impact on CO_2 emissions will be extensive with the continuous expansion of the scale of urban economy [8].

The urbanization process is not only reflected in greater overall economic strength but it also encompasses energy, the environment, and other dimensions. From the onset of the 21st century, urbanization has expanded concurrently with China's economic advancement along with a surge in energy consumption [7]. During the period 1978–2016, China's total energy consumption increased from 571.44 million tons to 4,358.19 million tons of standard coal at an average annual growth rate of 5.5% [4]. Fast-paced urbanization contributes significantly to rising energy demands. Energy-intensive economic activities (e.g., manufacturing and transportation), which are driven primarily by fossil fuels and contribute to environmental degradation, may also be widespread in urban areas [9].

Starting with the 12th Five-year Plan (2011–2015), the Chinese government has increasingly emphasized a strategy to expand domestic demands, especially those related to residential consumption to stabilize economic growth. Therefore, residential energy consumption and CO_2 emissions from residential consumption have emerged as important considerations in analyses of the drivers of CO_2 emissions [10]. In some developing countries, residential energy consumption has exceeded industrial energy consumption since the 1990s and has been an important driver of the growth of CO_2 emissions [11]. There are direct as well as indirect forms of energy consumption and CO_2 emissions from residential consumption. During the period 2000–2010, indirect energy consumption and CO_2 emissions from residential consumption were the main components of China’s total energy consumption and CO_2 emissions (69–77% and 77–84%, respectively) [12]. The energy consumption and CO_2 emissions of China’s urban population will inevitably increase over time with continually expanding urbanization. As the end consumers of industrial products, urban residents will significantly influence the design and creation of products and concepts within industrial enterprises, according to their carbon-related value orientations. Therefore, future urbanization and consumption trends of urban residents will gradually become the main determinants of China’s CO_2 emission growth.

In the context of economic globalization, China's economy has grown rapidly to become one of the most advanced economies globally. China is the largest developing country and is also the largest CO_2 emitter [13]. In 2016, China's CO_2 emissions were nearly double those of the United States [14]. Given the increasingly serious threat posed by climate change, energy conservation and emission reduction in China have become imperative. China’s reduction of its CO_2 emissions would significantly contribute to efforts to solve the problem of climate change and to develop a green and sustainable global economy [15]. Accordingly, China, as a major carbon emitter, needs to assume a larger share of international responsibility. In the context of the 2009 Copenhagen Accord, the Chinese government pledged to reduce the country's carbon intensity by 40–45% from its 2005 level by 2020 [16]. Furthermore, in the 2015 Paris Agreement, China pledged to achieve peak CO_2 emissions and to reduce its emissions per GDP by 60–65% from the 2005 level by 2030. China also aims to increase the share of non-fossil fuels in primary energy consumption to approximately 20% by 2030.

1.2 Literature review

Many studies have applied various types of decomposition analysis to evaluate the drivers of China’s extensive CO_2 emissions. Considering the spatial dimension, we subdivided previous studies focusing on China into two categories: national and provincial. Table 1 presents a summary of studies that applied decomposition analysis to China's CO_2 emissions, followed by a selective review of this literature.[1]

1.2.1 National-level studies

China's rapid development process has intensified the contradiction between economic growth and environmental sustainability. In the context of climate change, many studies have focused on the critical issue of China's carbon reduction, with energy consumption and production featuring prominently in analyses of CO_2 emissions. Given China's extensive energy consumption, Xu et al. [17] applied the logarithmic mean Divisia index (LMDI) method to decompose CO_2 emissions into energy structure, energy intensity, the industrial structure, economic outputs, and population scale effects for the period 1995–2011. They found that the energy intensity effect was the main factor inhibiting CO_2 emissions. Coal and thermal power generation are the primary components of China's energy consumption structure. Xie et al. [18] applied the Tapio decoupling indicator and LMDI method to evaluate the relationship between CO_2 emissions from the power sector and GDP. They found that whereas the intensity and consumption of energy in power generation promoted a decoupling of CO_2 emissions in the power industry and China's GDP, the scale of the economy and electrification were the two main factors inhibiting this decoupling.

Given the centrality of China's industrial sector in the production of CO_2 emissions, quantitative analyses of drivers of CO_2 emissions within this sector provide valuable inputs that can facilitate its carbon reduction. The chemical industry subsector is the second largest industrial source of CO_2 emissions in China. Lin and Long [19] employed the LMDI method to identify factors influencing energy usage and CO_2 emissions within China's chemical industry subsector. Their findings indicated that decreases in CO_2 emissions were related to energy intensity and the energy structure. The construction sector is also one of the most significant sources of CO_2 emissions. Wu et al. [20] showed that during the period 2000–2015, the most effective strategies for reducing CO_2 emissions during building operations entailed increasing development density, and improving carbon intensity,

[1] We acknowledge that many decomposition studies have been conducted on the CO_2 emissions of various countries and regions, worldwide. However, here we focus on studies relating to China.

Table 1 Studies using decomposition methods for examining CO_2 emissions and related topics in China (in chronological order).

Literature	Region	Period	Decomposition method [a,b]	Decomposed variables and decomposition factors
Xu et al. [17]	China	1995–2011	IDA (LMDI)	· CO_2 emissions from energy consumption · Five factors: energy structure, energy intensity, industrial structure, economic outputs, and population scale
Lin and Long [19]	30 provinces	1980–2011	IDA (LMDI)	· Changes in CO_2 emissions in the chemical industrial sector · Five factors: emission coefficient, energy structure, energy intensity, output per worker, and expansion scale
Wu et al. [20]	China	2000–2015	IDA (LMDI)	· CO_2 emissions from the construction sector · Seven factors: emission factor, industrial structure, energy structure, energy demand from appliances, floor space, infrastructure capacity, infrastructure development, and road length
Zhao et al. [21]	Shanghai	1996–2007	IDA (LMDI)	· Industrial CO_2 emissions · Four factors: energy mix, energy intensity, industrial structure, and industrial outputs
Tan et al. [22]	China	1998–2008	IDA (LMDI)	· CO2 emission intensity · Six factors: CO_2 emission coefficient, energy intensity of power generation, power generation and consumption ratio, electricity intensity of the GDP, provincial structural changes, and the energy intensity of the GDP for other activities
Wu and Zeng [23]	Shijingshan District of Beijing	2005–2015	IDA (LMDI)	· CO_2 emission intensity · Four factors: industrial structure, industrial energy intensity, energy structure, and emission coefficient
Ren et al. [24]	China	1996–2010	IDA (LMDI)	· Total CO_2 emissions from the manufacturing sector · Five factors: industrial structure, economic outputs, energy structure, energy intensity, and emission factors
Wang et al. [25]	30 provinces	2005–2010	Production-theoretical decomposition	· Provincial total CO_2 emissions · Seven factors: Changes in potential carbon factors, potential energy intensity, GDP, technical efficiency relating to CO_2 emissions, carbon abatement technology, technical efficiency relating to energy usage, and energy savings technology
Xie et al. [26]	China	1995–2013	IDA (LMDI)	· Changes in energy-related CO_2 emissions from China's petroleum refining and coking industrial sector · Five factors: effects of emission coefficients, energy structure, energy intensity, industrial activity, and the, industrial scale
Zhang et al. [27]	29 provinces	1995–2012	IDA (LMDI)	· CO_2 emissions · Four factors: carbon density, energy structure, energy proportion, and residual components
Wang and Feng [28]	China and 30 provinces	2000–2014	IDA (LMDI)	· National carbon emissions and provincial carbon emissions · Six factors: effects of population, economic outputs, industrial structure, energy intensity, energy structure, and CO_2 emission coefficient
Ye et al. [29]	30 provinces	1996–2013	Two-layer LMDI model	· Provincial CO_2 emissions from production and consumption · Four factors: economic outputs, industrial structure, energy intensity, and energy structure of seven economic sectors (production) · Four factors: population, urbanization, energy intensity, and energy structure of rural and urban household sectors (consumption)

Zang et al. [30]	Shanxi	1995–2014	IDA (LMDI)	• Direct residential carbon emissions • Seven factors: the number of households, per capita household income, household size, urbanization, energy intensity, energy structure, and emission coefficient
Pan et al. [31]	Northeastern region, Central region, Western region, Coastal region	2002–2010	SDA	• CO_2 emissions • Three factors: carbon emissions intensity, production technology, and final demand
Shi et al. [32]	Beijing, Tianjin, Shanghai, Chongqing	2010–2015	IDA (LMDI)	• Per capita urban CO_2 emissions • Nine factors: energy emissions, energy intensity, per capita energy emissions in the manufacturing and transportation sectors, transportation energy intensity and per capita vehicles; energy emissions, energy intensity, and per capita building areas in the construction sector
Xie et al. [18]	China	1985–2016	IDA (LMDI)	• CO_2 emissions from the power sector • Seven factors: energy consumption, thermal power structure, power generation structure, transmission and distribution loss, electrification, energy intensity, and economic scale
Liao et al. [33]	30 provinces	2004–2014	IDA (LMDI)	• CO_2 emissions from the power sector • Seven factors: energy structure, energy intensity, electrical structure, proportions of generation and consumption, industrial intensity, industrial structure, and economic scale
Feng et al. [34]	Guangdong	1995–2015	LMDI (IDA)	• CO_2 emissions • Five factors: carbon intensity, energy structure, energy intensity, economic growth, and population growth
Ma et al. [35]	China	2005–2016	IDA (LMDI)	• CO_2 emissions • Six factors: emission factor, energy structure, energy intensity of the industry, industrial structure, economic outputs, and population scale
Zhang et al. [36]	China	2000–2016	IDA (LMDI)	• CO_2 emissions • Six factors: emission coefficient, inter-energy consumption structure, energy intensity, industrial structure, economic activity, and population growth
Guo and Meng [37]	Beijing, Tianjin, Hebei	1995–2016	IDA (LMDI)	• CO_2 emissions from the transport sector • Six factors: energy structure, transportation energy intensity, transportation ratio, freight turnover of unit industrial outputs, industrialization, and the economy
Zheng et al. [38]	Beijing-Tianjin, North and Northeast China, Central and South Coasts, Central, Southwest, and Northwest China	2000–2016	IDA (LMDI)	• CO_2 emissions • Seven factors: population variations, economic growth, regional structure adjustment, energy efficiency improvement, industrial structure upgrades, energy mix, and changes in emission intensity
Wang et al. [39]	China	2000–2015	SDA	• Total household CO_2 emissions • Six factors: carbon intensity, structural change, rural consumption, urban consumption, population, and urbanization
Xia et al. [40]	China	1995–2009	SDA	• Indirect CO_2 emissions from household consumption • Six factors: direct carbon emissions coefficient, technology, urbanization rate, urban population, consumption composition, and per capita consumption
Cao et al. [41]	China and 30 provinces	2007–2012	SDA	• National and regional carbon intensities • Three factors: intensity (or efficiency), input structure, and final demand

Wang et al. [42]	Beijing, Tianjin, and Hebei	2002–2012	SDA	· Indirect carbon emissions from urban and rural residential consumption · Five factors: emission intensity, intermediate demand, consumption structure, consumption level, and population size

Notes: [a]: This column only focuses on decomposition methods, although alternative methods were also applied in some studies.
[b]: IDA: index decomposition analysis; LMDI: logarithmic mean Divisia index; SDA: structural decomposition analysis.

the energy structure, and the industrial structure within the construction sector.

Differing from traditional research focusing on the impacts of the industrial sector on CO_2 emissions, an increasing number of studies have evaluated the impacts of urbanization and residential consumption on CO_2 emissions. Ma et al. [35] showed that rapid economic development and accelerated urbanization counter a reduction in CO_2 emissions. This finding was confirmed by Wang et al. [39], who found that urbanization and changes in consumption patterns contributed to CO_2 emissions. Advancing urbanization not only increases households' incomes but it also promotes their consumption, thereby constituting a new source of CO_2 emissions. Xia et al. [40] examined the impacts of residential consumption on indirect CO_2 emissions using a combination of multivariate regression analysis with structural decomposition analysis (SDA). They attributed the increase in indirect CO_2 emissions primarily to urban employment, rapid urbanization, and the two-child policy.

1.2.2 Provincial-level studies

The impacts of economic development at the provincial level on CO_2 emissions are increasingly evident in light of the continuous expansion of the national economy. Therefore, studies on the role of changing patterns of provincial development in China provide valuable inputs for strategies aimed at decreasing CO_2 emissions. Zheng et al. [38] conducted a LMDI decomposition analysis of CO_2 emissions across 30 Chinese provinces divided into eight regions: Beijing-Tianjin, North and Northeast China, the Central and South Coasts, and Central, Southwest, and Northwest China. They found that the drivers of changes in CO_2 emissions varied across regions because of differences in their development patterns. Moreover, whereas the industrial structure and energy mix inhibited emissions at the national scale, they prompted increased emissions in some regions. Cao et al. [41] also focused on the same eight regions, using an extended multiplicative SDA method to identify the drivers of national and regional changes in carbon intensity at multiple levels. They divided these eight regions into two groups based on the results. In the first group comprising Northwest and Northeast China and the South Coast, carbon intensity increased because of the input structure and final demand effect; and in the second group comprising the remaining regions, carbon intensity decreased because of intensity and final demand effects.

National economic policies also have significant impacts on provincial emissions. In light of their analysis of provincial data, and considering the national economic strategy, Pan et al. [31] divided

China into four regions and analyzed factors influencing inter-regional CO_2 emissions using the SDA method. They found that final demands have the greatest positive influence on CO_2 emissions. A further finding following the decomposition of final demands was that after the financial crisis of 2007–2008, investments became the key driver, with the impacts of residential consumption on China's CO_2 emissions remaining marginal. However, the findings of studies on the effects of residential consumption on CO_2 emissions differ. For example, Wang et al. [42] found that the carbon emission intensity and the level of residential consumption were the main factors influencing indirect CO_2 emissions from 2002 to 2012 in the Beijing–Tianjin–Hebei region.

The impacts of economic development and industrial production on CO_2 emissions are relatively more direct, as evidenced in several studies. Wang et al. [25] decomposed changes in CO_2 emissions across 30 provinces into seven drivers using a new method of production-theoretical decomposition. They found that economic development, energy structure, and energy efficiency were positive drivers, whereas technological advancement, energy intensity, and carbon emission efficiency were negative drivers of CO_2 emissions. Zhao et al. [21] used the LMDI method to analyze the main drivers of industrial carbon emissions in Shanghai during the period 1996–2007. They identified industrial outputs as the main factor propelling industrial CO_2 emissions, whereas the key determinants of the reduction of industrial CO_2 emissions were energy intensity and the adjustment of energy sources and of the industrial structure. Shi et al. [32] conducted four case studies of hierarchical Chinese megacities (Beijing, Tianjin, Shanghai, and Chongqing) in which they decomposed per capita urban carbon emissions into the manufacturing, transportation, and construction sectors. They found that the development of the manufacturing sector and improvements in residents' living standards led to increases in CO_2 emissions in these cities.

Given that China is the most populous country in the world, some studies have examined the impacts of demography on CO_2 emissions. Li and Zhou [43] applied panel cointegration modeling to test long-term relationships between CO_2 emissions and variables of the demographic structure in Central, Eastern, and Western China. Their results indicated that there were long-term relationships between CO_2 emissions and the demographic structure at both regional and national levels. Moreover, Feng et al. [34] applied the LMDI method to investigate the drivers of CO_2 emissions in Guangdong Province, which had the largest permanent population among Chinese provinces in 2018. They concluded that both economic and demographic growth had a positive impact on CO_2 emissions in the province.

Existing studies on the impacts of urbanization and residential consumption on CO_2 emissions have mainly focused on individual provinces as opposed to considering all provinces. For example, Zang et al. [30] applied the LMDI approach to analyze the effects of urbanization and household-related factors on residents' direct CO_2 emissions in Shanxi Province. The results demonstrated that shrinking household size was a key constraining factor, whereas the expansion of urbanization contributed marginally to increased emissions. Using the IPAT (impact, population, affluence, and technology) model and considering provincial differences, Wang et al. [7] analyzed the impacts of urbanization on energy consumption and CO_2 emissions. Their findings indicated that the impacts of urbanization on provincial CO_2 emissions were closely related to industrial structures, energy efficiency levels, and developmental stages.

1.3 Purpose of this study

This review of the literature reveals some insights on the drivers of CO_2 emissions within China at national and provincial scales. Most of these earlier studies focused on economic development, energy consumption, and industrial sectors. However, a few studies systematically evaluated the drivers of CO_2 emissions in specific administrative units [44,45]. To the best of our knowledge, however, no previous studies have evaluated the impacts of urbanization on CO_2 emissions for the entire spectrum of provincial administrative units in China.

The impacts of urbanization on CO_2 emissions are multiple and complex, and vary according to the stage of urbanization [46]. To advance scientific knowledge regarding the impacts of urbanization on CO_2 emissions from the perspective of residential consumption, we evaluated the impacts of urbanization on changes in CO_2 emissions during the period 1990–2016. We applied a six-factor LMDI decomposition approach (using carbon and energy intensity, consumption inhibition, residential consumption, population urbanization, and population size) in 30 provincial administrative units (hereafter, provinces) across China. Considering the issues of feasibility of data collection and representative regional characteristics, we ultimately chose Chinese provinces as the geographical study locations.[2] In light of our decomposition analysis of 30 provinces, we elucidated the changing characteristics of the six driving factors. Our findings are of considerable value for improving the viability and application of effective strategies for reducing CO_2 emissions in China by accounting for regional differences and promoting economic and societal low-carbon development. Furthermore, urbanization is an ongoing global issue, particularly in developing countries, and will advance in the future. Therefore, the results of this study can provide insights with international applicability for reducing CO_2 emissions, especially in other developing countries. The reminder of this paper is organized as follows. Section 2 discusses the study methodology and data, section 3 presents the results and discussion, and section 4 presents the study's conclusions.

[2] Because of constraints relating to data collection, we did not include the Tibet Autonomous Region or the Special Administrative Regions of Hong Kong and Macao. See Fig. A1 in the Appendices for the geographical coverage of the study.

2. Methodology and data

Using provincial level data for the period 1990–2016, we applied the LMDI approach to conduct a quantitative evaluation of the impacts of urbanization on CO_2 emissions from the perspective of residential consumption. Figure 1 depicts the analytical structure. We defined three major decomposition categories: energy, consumption, and population. Accordingly, we identified six factors (carbon intensity, energy intensity, consumption inhibition, residential consumption, population urbanization, and population size) to explore their impact on CO_2 emissions. The connections of residential consumption and population urbanization to the overall urbanization process were particularly strong.

2.1 The LMDI decomposition method

Decomposition analysis is a mainstream method used for the quantitative measurement of the contribution of factors driving energy consumption and CO_2 emissions [47]. Commonly used decomposition methods include index decomposition analysis (IDA) and SDA. Because IDA is based on terminal output data, it is easier to conduct an analysis using a smaller data sample. Therefore, IDA was adopted in this study. LMDI, which is a variant of IDA, is a decomposition method entailing few variables and involving a time series. Because this modelling method does not rely on input–output data, it has gained in popularity since 2000 [48]. Therefore, we chose LMDI as the research method.

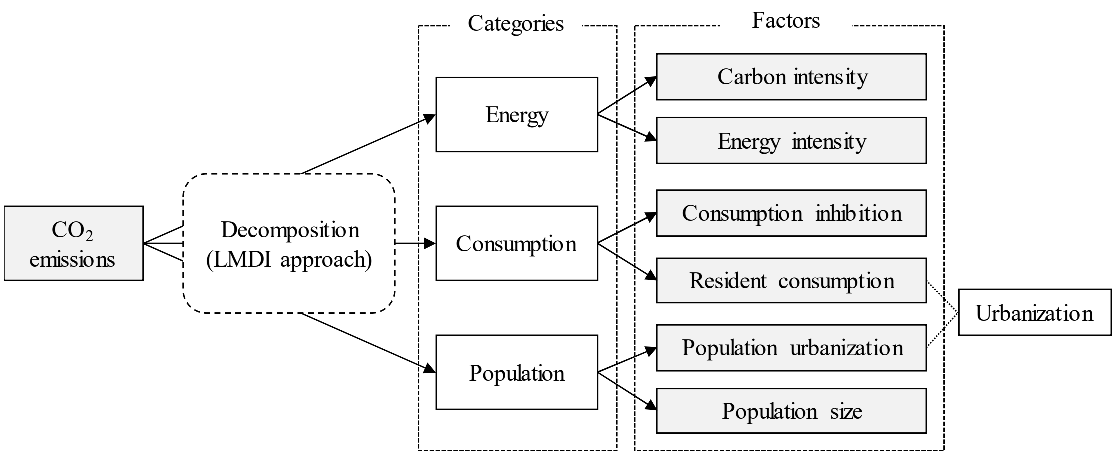


Figure 1. Structure of the decomposition analysis.

Note: The factors shaded in gray were used for the decomposition calculation.

Considering the Kaya identity, we decomposed CO_2 emissions as follows:

$$CARB_i = \frac{CARB_i}{ENE_i} \times \frac{ENE_i}{GRP_i} \times \frac{GRP_i}{POP_i} \times POP_i \tag{1}$$

where *CARB* denotes CO_2 emissions (in units of 10,000 tons), *ENE* denotes total energy consumption (10,000 tons of standard coal), *GRP* denotes the gross regional product (GRP; one hundred million yuan),[3] *POP* denotes the population (in units of 10,000 people), and *i* denotes 30 provinces.

Because our aim was to analyze the impacts of relevant factors on CO_2 emissions, focusing mainly on urbanization, we incorporated residential consumption and population urbanization factors in the traditional Kaya identity and further expanded them in a vector form to include urban and rural areas. Consequently, we inserted residential consumption (*RES*) into eq.1 as follows:

$$CARB_i = \frac{CARB_i}{ENE_i} \times \frac{ENE_i}{GRP_i} \times \frac{GRP_i}{RES_i} \times \frac{RES_i}{POP_i} \times POP_i \tag{2}$$

The urbanization process can be conceived simplistically as a process whereby the agricultural population is constantly transitioning into the non-agricultural population. Therefore, considering the urban–rural population structure, we subdivided *RES* and *POP* into their urban and rural components. Thus, *RES_r* and *RES_u* denoted resident consumption in rural and urban areas, respectively. Similarly, *POP_r* and *POP_u* denoted the rural and urban populations, respectively. Accordingly, we expressed *RES* as follows:

$$RES_i = \left(\frac{RES\_u_i}{POP\_u_i} \frac{RES\_r_i}{POP\_r_i} \right) \times \begin{pmatrix} \dfrac{POP\_u_i}{POP_i} \\ \dfrac{POP\_r_i}{POP_i} \end{pmatrix} \times POP_i \tag{3}$$

We subsequently plugged eq. 3 into eq. 2 to obtain the following equation:

3 For the national calculation, GDP was used instead.

$$CARB_i = \frac{CARB_i}{ENE_i} \times \frac{ENE_i}{GRP_i} \times \frac{GRP_i}{RES_i} \times \left(\frac{RES\_u_i}{POP\_u_i} \frac{RES\_r_i}{POP\_r_i} \right) \times \left(\begin{array}{c} \frac{POP\_u_i}{POP_i} \\ \frac{POP\_r_i}{POP_i} \end{array} \right) \times POP_i$$
$$= C\_int_i \times E\_int_i \times C\_inb_i \times \left(PC\_con\_u_i \; PC\_con\_r_i \right) \times \left(\begin{array}{c} P\_pop\_u_i \\ P\_pop\_r_i \end{array} \right) \times POP_i \tag{4}$$

where *C_int* denotes carbon intensity (*CARB*/*ENE*), *E_int* denotes energy intensity (*ENE*/*GRP*), *C_inb* represents the inhibition of consumption (*GRP*/*RES*), *PC_con_u* (*PC_con_r*) refers to urban (rural) per capita consumption (*RES_u*/*POP_u* (*RES_r*/*POP_r*)), and *P_pop_u* (*P_pop_r*) refers to the proportion of the urban (rural) population in relation to the total population (*POP_u*/*POP* (*POP_r*/*POP*)). $S\_u_i = (R\_con\_u_i \times P\_pro\_u_i) / (R\_con\_u_i \times P\_pro\_u_i + R\_con\_r_i \times P\_pro\_r_i)$, which denotes the proportion of the consumption of urban residents in relation to the total consumption of the province, was plugged into eq. 4, as follows:

$$\begin{aligned} CARB_i &= C\_int_i \times E\_int_i \times C\_inb_i \times P\_con\_u_i^{S\_u_i} \times P\_con\_r_i^{1\text{-}S\_u_i} \\ &\times PC\_con\_u_i^{S\_u_i} \times PC\_con\_r_i^{1\text{-}S\_u_i} \times P\_pop\_u_i^{S\_u_i} \times P\_pop\_r_i^{1\text{-}S\_u_i} \times POP_i \end{aligned} \tag{5}$$

where *P_con_u* (*P_con_r*) refers to the inverse of the proportion of the urban (rural) consumption in relation to the total consumption (*RES*/*RES_u* (*RES*/*RES_r*)).

This equation shows the product form of CO_2 emissions. Applying the LMDI approach (additive form [49]), we obtained the effect of each factor on CO_2 emissions (eqs. 6–11). Equation 5 decomposes CO_2 emissions at one point in time, whereas eq. 6 decomposes differences in CO_2 emissions between two time points.

Total effect:

$$\Delta CARB_i^T = CARB_i^T - CARB_i^0 = (7) + (8) + (9) + (10) + (11) + (12) \tag{6}$$

Carbon intensity effect:

$$\Delta CARB_{C\_int,i}^{T} = \frac{CARB_i^T - CARB_i^0}{\ln CARB_i^T - \ln CARB_i^0} \times \ln \frac{C\_int_i^T}{C\_int_i^0} \tag{7}$$

Energy intensity effect:

$$\Delta CARB_{E\_int,i}^{T} = \frac{CARB_i^T - CARB_i^0}{\ln CARB_i^T - \ln CARB_i^0} \times \ln \frac{E\_int_i^T}{E\_int_i^0} \tag{8}$$

Consumption inhibition effect:

$$\Delta CARB_{C\_inb,i}^{T} = \frac{CARB_i^T - CARB_i^0}{\ln CARB_i^T - \ln CARB_i^0} \times \ln \frac{C\_inb_i^T}{C\_inb_i^0} \tag{9}$$

Resident consumption effect:

$$\Delta CARB_{R\_con,i}^{T} = \frac{CARB_i^T - CARB_i^0}{\ln CARB_i^T - \ln CARB_i^0} \times \left[\begin{array}{l} S\_u_i^0 \ln \dfrac{P\_con\_u_i^T}{P\_con\_u_i^0} + \left(1 - S\_u_i^0\right) \ln \dfrac{P\_con\_r_i^T}{P\_con\_r_i^0} \\ + S\_u_i^0 \ln \dfrac{PC\_con\_u_i^T}{PC\_con\_u_i^0} + \left(1 - S\_u_i^0\right) \ln \dfrac{PC\_con\_r_i^T}{PC\_con\_r_i^0} \end{array} \right] \tag{10}$$

Population urbanization effect:

$$\Delta CARB_{P\_urb,i}^{T} = \frac{CARB_i^T - CARB_i^0}{\ln CARB_i^T - \ln CARB_i^0} \times \left[S\_u_i^0 \ln \frac{P\_pop\_u_i^T}{P\_pop\_u_i^0} + \left(1 - S\_u_i^0\right) \ln \frac{P\_pop\_r_i^T}{P\_pop\_r_i^0} \right] \tag{11}$$

Population size effect:

$$\Delta CARB_{POP,i}^{T} = \frac{CARB_i^T - CARB_i^0}{\ln CARB_i^T - \ln CARB_i^0} \times \ln \frac{POP_i^T}{POP_i^0} \tag{12}$$

$\Delta CARB_X$ shows six factors (X) entailed in the decomposition analysis. The superscripts 0 and T in the above equations denote the base year (1990) and the calculation period, respectively. $S\_u_i^0$ was applied instead of $S\_u_i^T$ to calculate the effects of residential consumption and of population urbanization (eqs. 10–11). To perform calculations of the differences between two periods, S_u_i was actually based on the point elasticity value during period 0, and the change in adjacent years was negligible. This means that the $S\_u_i^0$ and $S\_u_i^T$ values for the adjacent years are approximately equal; the change effect for non-adjacent years can be obtained by summing up that of adjacent years between the 0 and *T* periods [49].

2.2 Data

We used available data for the period 1990–2016. Relevant data (i.e., *ENE*, *GDP*, *RES_u*, *RES_r*, *POP_u*, and *POP_r*) were extracted from the official provincial statistical yearbooks (see Table A1 in the Appendix for the data sources). The statistical yearbooks do not include CO_2 emissions data; we therefore calculated the amount of CO_2 emissions per province using energy consumption data extracted from the statistical yearbooks as follows [50]:

$$CARB_i = \sum CARB_{ij} = \sum FUEL_{ij} \times SC_j \times SEC_j \times \frac{44}{12} \tag{13}$$

where *FUEL* denotes the total consumption of different energy types (in tons), *SC* denotes the conversion coefficient of standard coal for different energy types (in units of 10,000 tons of standard coal per ton of energy), *SEC* is the carbon emission coefficient (in tons of carbon per ton of standard coal), and *j* represents different types of fossil fuels (Table 2). Table 2 shows the corresponding values of *SC* and *SEC* by energy type.

Table 2 Standard coal conversion and carbon emission coefficients.

Energy type	Standard coal conversion coefficient (ton of standard coal/ton of energy)	Carbon emission coefficient (ton of carbon/ton of standard coal)
Coal	0.7143	0.7559
Coke	0.9714	0.855
Crude oil	1.4286	0.5857
Fuel oil	1.4286	0.6185
Gasoline	1.4714	0.5538
Kerosene	1.4714	0.5714
Diesel	1.4571	0.5921
Natural gas	1.33×10^{-3}	0.4483
LPG	1.7143	0.5042

Sources: National Bureau of Statistics of China [4] and Intergovernmental Panel on Climate Change [50].

National-level data, such as population size, residential consumption, and GDP were extracted from published issues of the China Statistical Yearbook [4]. As shown in Table 3, the growth rate of the urban population exceeds that of the total population, whereas the rural population is decreasing annually, reflecting a constant trend of rapid urbanization in China in alignment with advancing economic development. However, because China's urbanization process initially progressed relatively slowly, the rural population base remains large, accounting for a high proportion of the population. By comparison, developed countries, such as the United Kingdom, have basically completed their industrialization and urbanization processes, with the level of urbanization exceeding 80% [51]. China's urbanization rate is therefore still low compared with those of developed countries.

Table 3 China's demographic and economic trends for the period 1990–2016.

	Year					
	1990	1995	2000	2005	2010	2016
Total population (in 10,000s)	114,333	121,121	126,743	130,756	134,091	138,271
Urban population rate (%)	26.4	29.0	36.2	43.0	50.0	57.4
Rural population rate (%)	73.6	71.0	63.8	57.0	50.1	42.7
Residential consumption (in hundred million yuan)	9,435	2,8073	46,988	75,232	146,058	293,443
Urban residential consumption rate (%)	44.5	58.9	66.8	72.2	77.0	78.1
Rural resident consumption rate (%)	55.5	41.1	33.2	27.8	23.0	21.9
GDP (in one hundred million yuan)	18,872	61,339	100,280	187,318	413,030	743,585
Ratio of residential consumption to the GDP	50.0	45.8	46.9	40.2	35.4	39.5

The growth rate of residential consumption significantly exceeds that of GDP, and the gap between urban and rural consumption is gradually widening. In recent years, urban consumption has constituted a majority share of the total consumption in China, suggesting that urban areas may have become the main drivers of CO_2 emissions. In the past, on the premise of stable growth of residential consumption and GDP, the ratio of residential consumption to the GDP decreased over time but has gradually risen in recent years. The most likely reason for this trend is that the Chinese government took measures to expand domestic demand further and to promote stable and rapid economic growth after 2008. Specifically, it changed the mode of economic development, reduced macro-control over the economy, and gradually restored the growth-inducing effect of consumption on the economy [52].

3. Results and discussion

In this section, we first discuss the national-level results of our decomposition analysis. We subsequently provide a detailed analysis of provincial-level data.

3.1 Drivers of changes in CO_2 emissions under conditions of urbanization at the national level

Figure 2 shows the results of the decomposition analysis of national-level data for China [4]. The overall trend was one of a rise in China's CO_2 emissions up to 2013, with an accelerated increase in emissions after 2000. The overall impact of energy intensity on the reduction of CO_2 emissions in China has been a stabilizing one. Since the launch of the 11th Five-Year Plan (2006–2010) when the Chinese government introduced a policy of energy conservation and emission reduction, significant improvements in energy efficiency have been evident, with the energy intensity effect gradually becoming stronger from around 2005, eventually emerging as the most important factor driving the reduction in China's CO_2 emissions. Another factor contributing to the reduction of CO_2 emissions is the carbon intensity effect. The proportion of coal within China's energy consumption structure decreased from 76.2% in 1990 to 62.0% in 2016 [4]. However, compared with the diversified and clean energy structure in developed countries, China's energy consumption remains highly dependent on high-carbon fuels. Therefore, the carbon intensity effect is relatively weak in China. However, a trend of gradual enhancement of this effect was evident after 2010. This is because during the period of the 12th Five-Year Plan, the Chinese government began to promote an optimized energy structure while regulating the growth of high-carbon energy sources, such as coal and oil, and encouraging diversified energy development.

As shown in Fig. 2, the continuous growth of CO_2 emissions is mainly caused by the positive residential consumption effect on CO_2 emissions. From Table 3, it is evident that the urban population is growing continuously, and is simultaneously driving the continuous increase in urban consumption. Population growth and rapid urbanization not only increase residential consumption demands but they also amplify the impacts of increasing production and indirect CO_2 emissions [40]. The proportion of indirect CO_2 emissions from consumer goods in relation to the total emissions rose from 58.7% in 1992 to 64.3% in 2005 [53]. In light of the considerable expansion potential of China's future urbanization, urban residential consumption may become a strong driver of CO_2 emissions over an extended period.

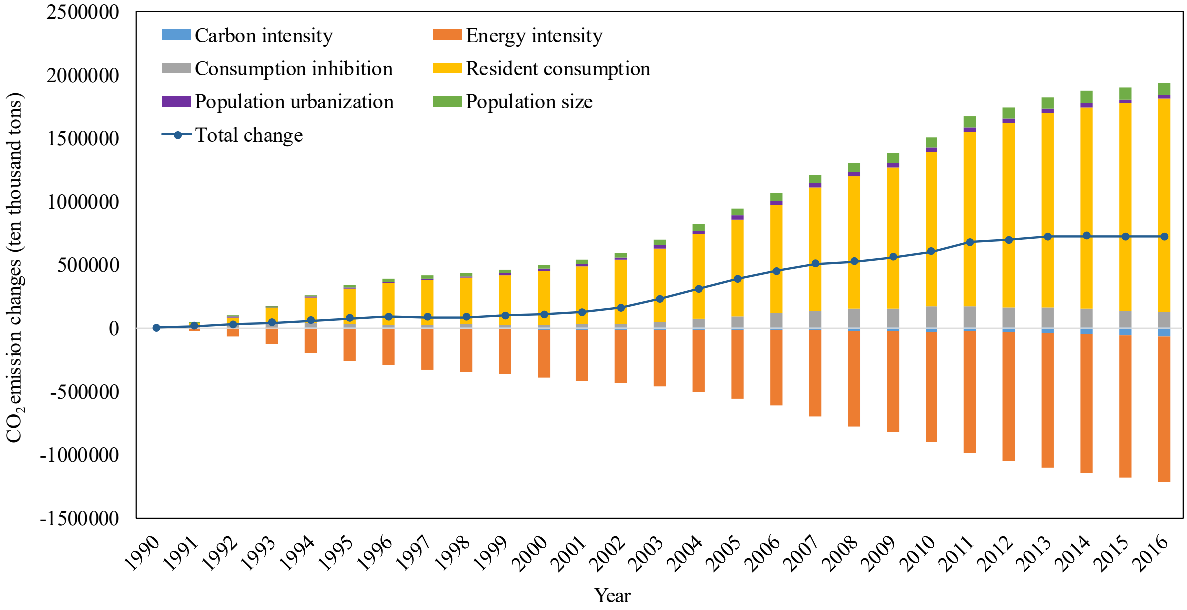


Figure 2. National-level results of the decomposition analysis. Emissions for each year are relative to those in 1990.

Currently, population urbanization and consumption inhibition effects are positively influencing the growth of China's CO_2 emissions. However, from around 2013, there has been a gradual weakening of these two effects. The effect of consumption inhibition reflects the degree of economic restraint on residential consumption. An increasing effect indicates a greater degree of restraint relating to residential consumption, whereas a decreasing effect indicates the expansion of residential consumption. During the period of the 12th Five-Year Plan, a strategic national policy has entailed expanding domestic demand, with the government gradually relinquishing its macro-control of the economy. This strategy, in turn, has promoted a decrease in the positive consumption inhibition effect on CO_2 emissions. Furthermore, in March 2014, the new national urbanization plan (2014–2020) was officially released. This plan seeks to transform the mode of urbanization development and to promote stable and sustainable development of a new mode of urbanization, resulting in the gradual weakening of the positive effect of an urbanizing population on CO_2 emissions.

3.2 Provincial-level drivers of changes in CO_2 emissions in the context of urbanization

3.2.1 The overall provincial trend relating to the six factors under investigation

In light of the preceding analysis of factors influencing CO_2 emissions based on national-level data, we now present an analysis of the factors influencing CO_2 emissions at the provincial level, which is the main topic of this paper (Fig. 3).[4] China is a large country with the third largest land area (evidenced by latitude and longitude coverage) in the world. Variations in population distribution, energy structures, and economic development are clearly discernable and are linked to natural geographical conditions. Therefore, regional differences should be considered in an analysis of the factors influencing CO_2 emissions in China. At the same time, we attempted to elucidate similarities and differences in results at the national and provincial levels, thereby addressing the shortcomings of previous studies that used country-level data, which yielded above-average results [35,49].

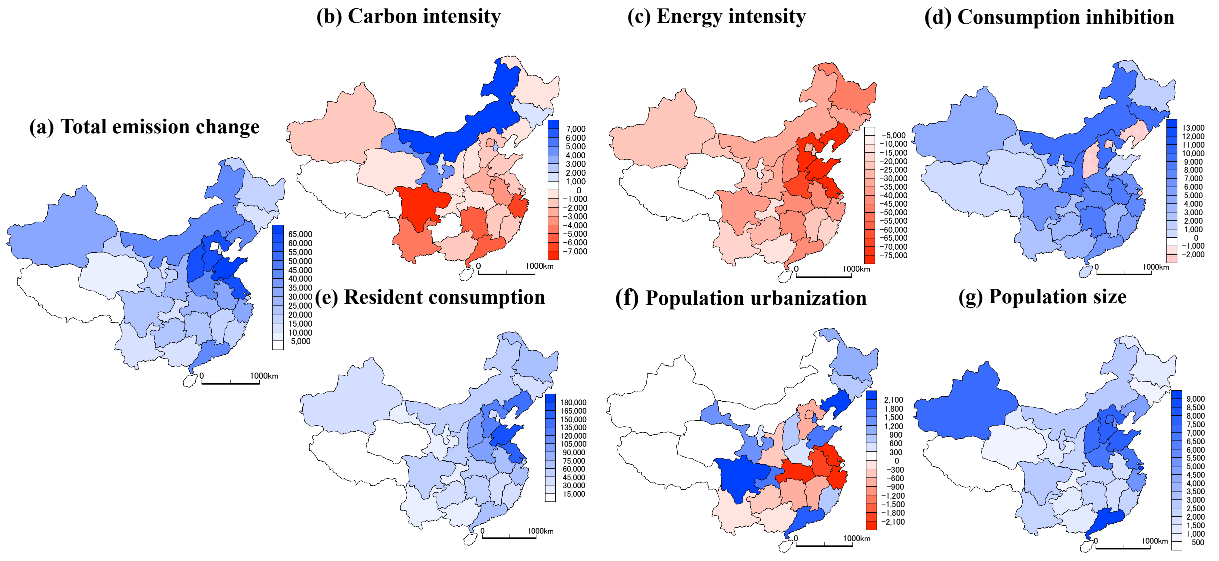


Figure 3. Changes in total CO_2 emissions (a) and the impacts of six factors on CO_2 emissions by province: carbon intensity effect (b), energy intensity effect (c), consumption inhibition effect (d), resident consumption effect (e), population urbanization effect (f), and population size effect (g) during the period 1990–2016 (unit: 1,000 tons of CO_2 emissions). See Fig.A1 for the geographical locations of the provinces.

Before presenting a detailed analysis aimed at eliciting a deeper understanding of changes in China's CO_2 emissions, we will first discuss changes in CO_2 emissions in the provinces during the period 1990–2016. Overall, while the CO_2 emissions in all of the provinces increased over time, changes in CO_2 emissions exhibited a specific distribution pattern. CO_2 emissions are evidently concentrated in

[4] All of the time-series for the provincial decomposition results are shown in Fig. A2 in the Appendix. Because the number of provinces was large, our analysis focused on representative provinces.

China’s four key industrial bases (in Central and Southern Liaoning, Beijing-Tianjin-Hebei, the Yangtze River Delta, and the Pearl River Delta[5]). Furthermore, CO_2 emissions are concentrated in China’s coal-rich regions, notably Shanxi, Shaanxi, Inner Mongolia, and Xinjiang in the north, and Guizhou in the south. The established coal reserves in these five provinces account for 81% of China’s total coal reserves [54]. The energy sector has been the industrial pillar in all five of these provinces and fuels economic development. The ratio of secondary industry in the GDPs of these five provinces is relatively high. For example, in 2011, the ratio of secondary industry to the GDP in Shanxi and Inner Mongolia reached the highest values of 58.6% and 55.9%, respectively, in recent years [55,56].

Fig. 3c, e, and g, reveals that the distributions of energy intensity, residential consumption, and population size effects exhibit similar patterns, being mostly concentrated in China's industrial bases and major energy-producing provinces. On the one hand, the urbanization process is more rapid in economically developed regions (e.g., Beijing and Shanghai) than in other regions, which would encourage innovations relating to production technology and promote population aggregation. On the other hand, advanced economic development continuously enhances residential consumption power, contributing to the accelerated growth of CO_2 emissions.

A comparison of carbon intensity effects at the provincial and national levels (Figs. 3f and 2, respectively) revealed some differences. At the national level, the carbon intensity effect has had a negative impact on CO_2 emissions since 1993. However, as Fig. 3b shows, there are still some provinces where the carbon intensity effect is positive, particularly in the northern areas. Examples include the northwestern provinces of Inner Mongolia and Gansu, which are relatively far into the interior and close to the plateau, with complicated terrains and inadequate access to transportation. Because of these unfavorable geographical conditions, the sustained backwardness of productive forces has resulted in these provinces lagging behind in terms of economic and other aspects of

[5] The first industrial base is located in central and southern Liaoning, with Liaonin Province at the center. It is dependent on its abundant resources and has a long history of industrial development, but it also demonstrates resource exhaustion and serious environmental pollution. Adjacent to this base is the second largest industrial base in China, covering Beijing, Tianjin, and Hebei (i.e., JingJinJi). The third industrial base is located in the Yangtze River Delta and encompasses highly advanced heavy and light industries in areas that include Shanghai, Jiangsu, and Zhejiang. The last base, characterized by light industry, is located in the Pearl River Delta with Guangdong at the center.

development [57]. However, both provinces are rich in coal resources. Consequently, their development has relied heavily on coal for their energy supplies, resulting in a positive carbon intensity effect.

The consumption inhibition effect was found to be positive in most provinces (Fig. 3d), whereas it was negative in economically developed regions, such as Beijing and Shanghai. Because of its special political situation, Beijing's development process has always been distinctive. The importance of foreign trade in Shanghai, which prompted the accelerated development of trade, stems from its advantage as a port city. Under China's reform and opening-up policy, Shanghai has attracted further foreign investment and its sustainable economic development has encouraged rapid urbanization. Like Beijing and Shanghai, Liaoning and Shanxi also demonstrated a negative consumption inhibition effect. However, they underwent a transformation, shifting from an industrial model that was over-reliant on energy development and government intervention to a new industrialization model. Both provinces contributed to revitalizing the market economy, actively stimulating consumption to expand domestic demand and transforming the pattern of urbanization development. [58]. Therefore, from the perspective of their urban development model, Shanxi and Liaoning differ from Beijing and Shanghai, although they have also achieved a negative effect.

A comparison of national-level and provincial-level results for the decomposition analysis revealed significant differences relating to changes in the population urbanization effect (Figs. 2 and 3f). This effect ultimately did not have a negative impact on CO_2 emissions in China as a whole (Fig. 2). The provincial distribution of a negative population urbanization effect (Fig. 3f) was mostly concentrated in southern China, and especially in the Yangtze River Delta. Most of these provinces are economically developed. However, in some areas, economic development has lagged behind, and a negative population urbanization effect is apparent. The national-level results reveal that the change in the population urbanization effect approximates an inverse U-shape. During the period 1990–2007, it showed an increasing trend. This is because following the introduction of the reform and opening-up process, the limited productivity that characterized the early stage of urbanization was resolved and the scale of production was expanded. Consequently, the concentration of the labor force in urban areas was increasingly evident and the population urbanization effect during this period showed a strong positive trend. However, because of an excessive emphasis on economic development, various problems relating to population urbanization manifested. For example, urbanization lagged behind industrialization and the development of urban infrastructure could not keep pace with the urbanization process. To achieve more sustainable development, the process of transforming urbanization began in areas demonstrating higher degrees of urbanization. The industrial structure of cities began to be transformed, and the ratio of secondary industry's GDP to the total GDP was reduced. High-tech industries were developed, and production-focused economic growth was transformed to stimulate consumption, with the aim of expanding domestic demand. During this period, the positive effect of population urbanization on CO_2 emissions gradually weakened. Because of regional differences in the degrees of urbanization, the urbanization effect of population was realized in some regions, which has had a negative impact on CO_2 emissions.

3.2.2 Impacts of energy and technology on changes in CO_2 emissions

While carbon and energy intensity have both had significant restraining effects on CO_2 emissions, the energy intensity effect has significantly exceeded the carbon intensity effect. As discussed in section 3.2.1, an analysis of the factors affecting China's CO_2 emissions should take regional differences into account. This consideration also applies in independent analyses of each effect.

Figure 3b shows that the carbon intensity effect was negative in most provinces. A geographic division of these regions reveals that the negative carbon intensity effect is more apparent in the southern region. This negative effect has mostly occurred in the southwestern region, which is characterized by particular geographical conditions, or in regions with developed economies. Southwest China has a humid climate and numerous abundantly flowing rivers with vertical drops. Therefore, this region is rich in hydropower resources. By contrast, provinces evidencing a positive or weakly negative carbon intensity effects are concentrated in North China. This may be because most of these provinces are major coal-producing areas. The distribution of coal resources in China is more concentrated in the northern and western regions than in the southern and eastern ones. In particular, North China accounts for 57.9% of China's coal reserves [54].

To illustrate the impact of regional energy characteristics on the carbon intensity effect more clearly, we will compare the cases of Sichuan and Inner Mongolia, which have energy supply structures that are representative of those in the southern and northern regions of China, respectively. Fig. 4 shows the decomposition results and energy structures in Sichuan and Inner Mongolia.

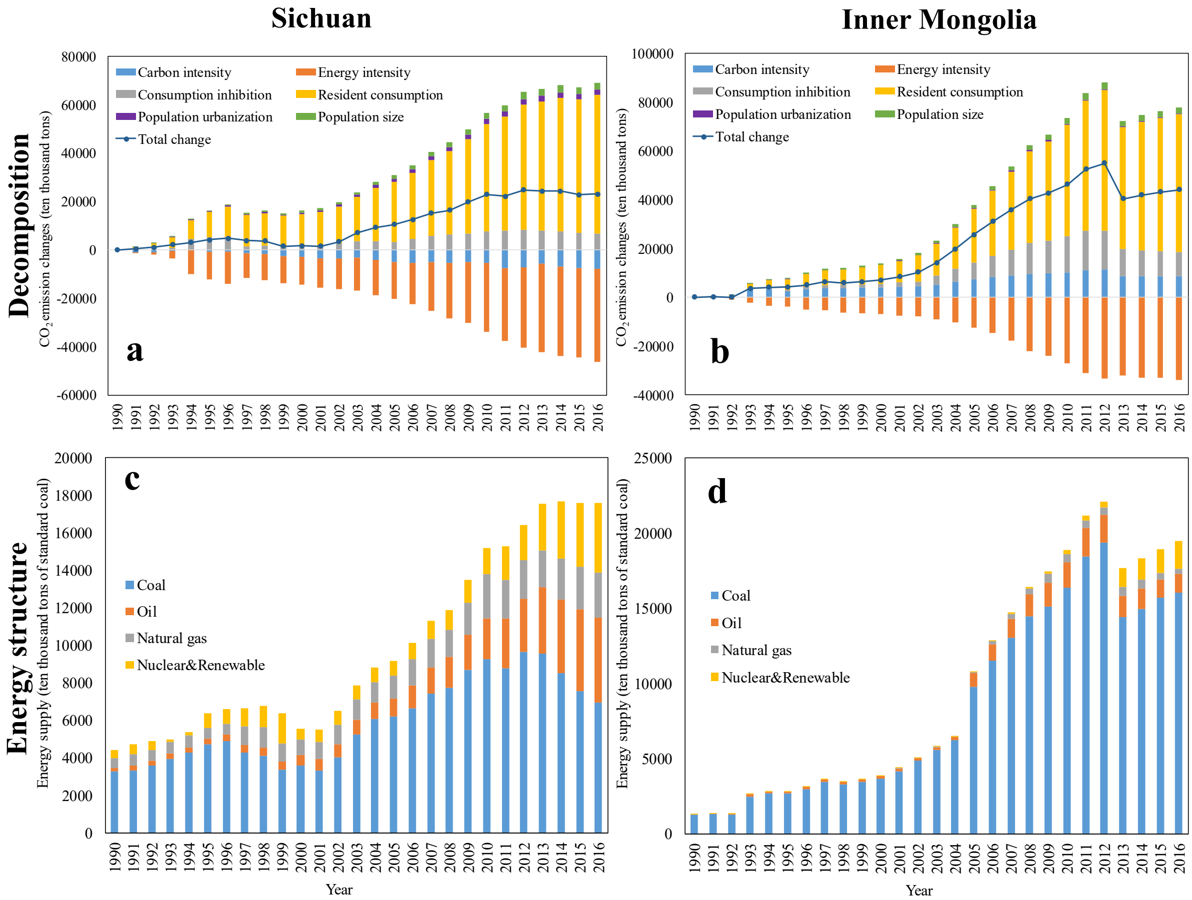


Figure 4. Decomposition results for Sichuan and Inner Mongolia (a and b) and their structures of energy supply (c and d).

Sichuan is the second largest provincial source of hydropower resources in China after Yunnan Province, and it also has the largest reserves of natural gas and the best conditions for their development [59]. As a major producer and consumer of clean energy, Sichuan is playing an important strategic role in the transformation of China's national energy structure and in the promotion of sustainable economic and social development. Inner Mongolia, which is located in the northern part of China, is the main domestic producer of China’s coal resources. It has a coal production capacity of 1.14 billion tons and produces 850 million tons of coal, accounting for about a quarter of the total national coal production [60]. In 2014, the coal industry accounted for 28.8% of the industrial GDP and contributed to 18% of economic growth [56]. Compared with the developed provinces, Inner Mongolia is highly dependent on the energy industry for its economic development.

The decomposition results for Sichuan (Fig. 4a) reveal that negative carbon intensity and energy intensity effects have increased over time and are the main forces restraining CO_2 emissions in

Sichuan. Whereas the carbon intensity effect evidenced frequent changes, it generally remained negative. Moreover, from 2011 onward, the negative carbon intensity effect increased significantly. The likely reason for this increase is that the Sichuan government set goals of developing clean and renewable energy, optimizing the energy consumption structure, and reducing the proportion of high-carbon fuels consumed in the 12th Five-Year Plan. Consequently, starting from 2006, there has been a significant and accelerating improvement in energy intensity. The transformation of traditional agriculture into modern agriculture and the rapid development of tertiary industry are the two key reasons for this improvement. Technological innovations have continued to be implemented within secondary industry, and energy efficiency has been further improved. Data extracted from the Sichuan Statistical Yearbook revealed fluctuations in the energy consumption of primary industry, ranging between 2.70 million tons and 3.14 million tons of standard coal during the period 2006–2016. However, the gross production of primary industry increased from 159.55 billion yuan to 392.41 billion yuan, indicating continuous improvements in the energy efficiency of primary industry [61]. The proportion of tertiary industry in the GDP rose from 38.2% to 45.4% during the same period, indicating that the economic structure of Sichuan has advanced. Energy consumption within the secondary industrial sector slowed down and declined after 2013, although the GDP has continued to demonstrate sustained growth.

In the case of Inner Mongolia, the carbon intensity effect was significantly positive. Differing from Sichuan, the energy intensity effect in this province entailed only a negative impact on CO_2 emissions (Fig. 4b). Coal consumption in Inner Mongolia accounts for a high proportion of energy consumption, and the proportion of coal shows an overall rising trend (Fig. 4d). Moreover, the penetration of clean energy has occurred at a very slow pace. Therefore, the strongly positive carbon intensity effect in Inner Mongolia is mainly attributable to its coal-dependent energy structure. From 2013 onward, the energy intensity effect has been stable. A comparison of energy intensity in and after 2012 revealed that there has even been a downward trend. During the period of the 12th Five-Year Plan, the Inner Mongolian government promoted the transformation of the industrial structure from being resource based to being non-resource based. The transformation and upgrading of the industrial structure has led to reduced energy consumption since 2012, and energy intensity has also slowed down.

3.2.3 Effects of consumption inhibition on changes in CO_2 emissions under different economic models

We focused in particular on the consumption inhibition effect in this study. The overall trend revealed through our analysis of national data (Fig. 2) closely resembled an inverse U-shape, which relates to China's economic development model. The results of the analysis of provincial data (Fig. 3d) showed a positive consumption inhibition effect in the most economically developed regions. However, in developing regions, because the economic driving force of investments exceeded that of consumption, the effect of consumption inhibition on CO_2 emissions was negative. Along with the overall increase in economic strength and the future transformation of the economic model, this negative effect will spread to more areas, as evidenced in developed countries [62].

We selected two provinces, Beijing and Henan, which have characteristics that are representative of China's economic development process. Because of its particular situation, Beijing has experienced accelerated development resulting from government interventions in its economy. Its urban economy has also reached an advanced stage associated with a shift in the mode of economic development toward sustainable development. Henan, which is China's most populous province, is a traditional agricultural province with a high proportion of primary industry and a slow-paced urbanization process. There are therefore clear differences in the economic development processes of these two provinces, which represent two different stages of China's economic development. Therefore, these two provinces were selected for a comparative analysis.

Investments are a major driver of growth in the modern economy. To accelerate economic development or achieve certain economic development goals, it is necessary to maintain a certain investment rate. As the largest developing country in the world, China's economic development is more inclined toward macro-control, and is relatively dependent on government expenditure, investments, and net exports. Therefore, the investment rates in most regions of China are at high levels, correspondingly inhibiting consumption that stimulates the economy. As noted in section 3.1, the consumption inhibition effect is closely related to the composition of the economy. Therefore, here we examine changes in various economic variables in Beijing and Henan (Fig. 5c and d). It is apparent from Fig. 5b, which shows the total amount of CO_2 emissions, and Fig. 5d, showing economic variables, that during years of relatively high investment rates, CO_2 emissions increased continually in Henan. Since 2003, the capital formation rate of Henan has increased rapidly, and the final consumption rate has significantly decreased. Moreover, Henan's CO_2 emissions began to increase around the same year. Since 2011, Henan's final consumption rate has shown an upward trend, and the growth rate of capital formation has gradually slowed down. During the same period, the growth rate of CO_2 emissions in Henan declined, and its emissions eventually stabilized.

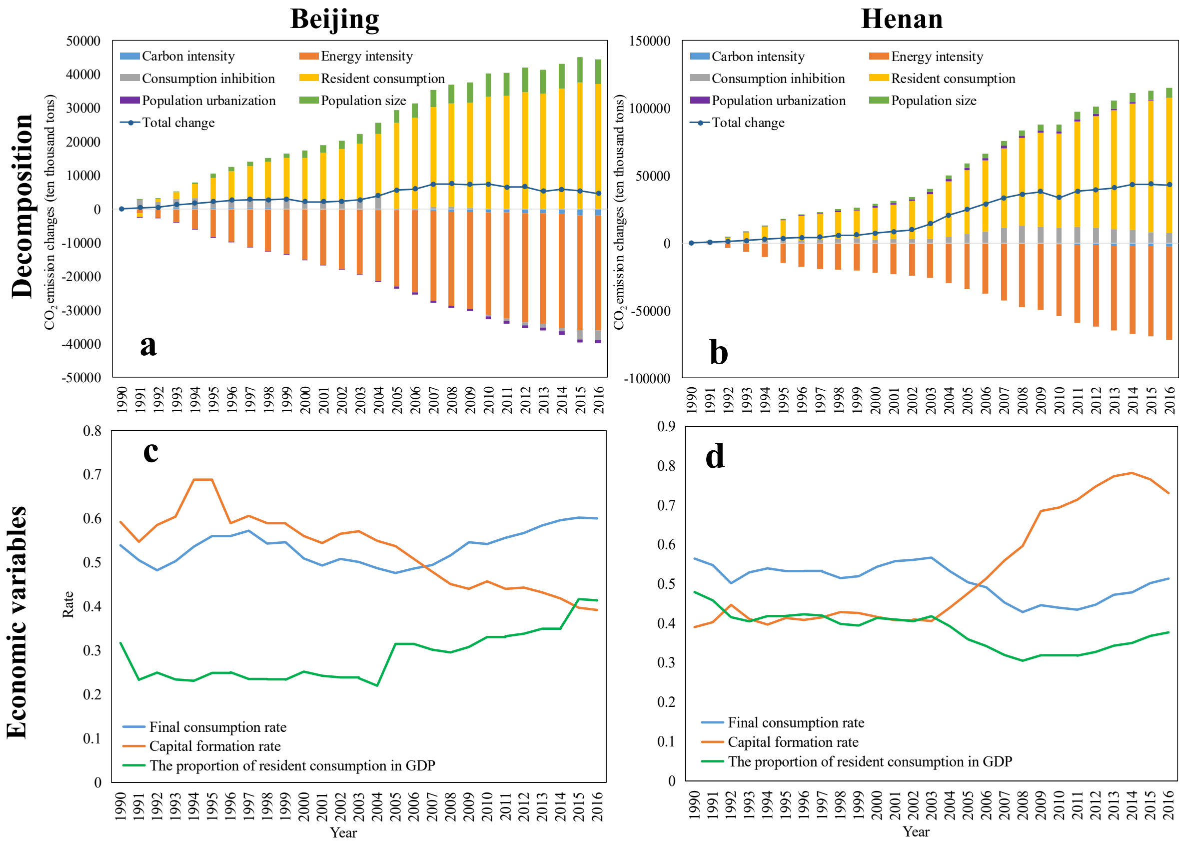


Figure 5. Decomposition results for Beijing and Henan and their economic variables.

The consumption inhibition effect is substantially affected by the adopted model of economic development. China's reform and opening-up policy, implemented in the late 20th century, enabled rapid economic development throughout the country. Beijing's investment rate peaked at 68.8% in 1994 (Fig. 5c), and both the scale of the expansion and the development of production and the market were unprecedented. During the same period, the positive effect of consumption inhibition also accelerated (Fig. 5a). However, in 1995, macro-control entered the "soft-landing" stage, and the investment rate decreased annually. Expanding domestic demand first appeared in planning content under the 11th Five-Year Plan, leading, in 2007, to a situation in which Beijing's consumption rate exceeded its investment rate (Fig. 5c). During the period of the 12th Five-Year Plan, the Chinese government proposed to accelerate the process of transforming the mode of economic development. Therefore, Beijing entered a period of economic transition. There was a greater focus on expanding Beijing's domestic demand and stimulating consumption to promote more stable and sustainable economic development [63]. Fig. 5c clearly shows that from 2010 onward, residential consumption increased rapidly while the final consumption rate continued to rise. The adoption of this model of economic development eventually resulted in a negative consumption inhibition effect.

By contrast, Henan experienced a positive consumption inhibition effect during the study period. At the onset of the 21st century, national regional economic policies, such as the Rise of Central China Policy,[6] enabled Henan's economy to progress gradually, finally entering a stage of accelerated development. However, because of its weak economic foundation, the initial stage of attracting investments proceeded slowly, and the rate of capital formation during this period remained lower than that of final consumption (Fig. 5d). However, the steady increase in the proportion of secondary industry resulted in a rapid rise in Henan's CO_2 emissions at the beginning of the 21st century, and around 2005, the capital formation rate rose above the final consumption rate (Fig. 5d). Supported by national preferential policies (e.g., the Rise of Central China Policy), Henan succeeded in attracting many industries that shifted there from eastern coastal areas. Consequently, Henan attracted more investments, and its capital formation rate began to rise (Fig. 5d). During this period, Henan acquired more developed production technology resulting from industrial transfers [64]. Notably, the growth of CO_2 emissions slowed down while the economy developed (Fig. 5b and d). In 2010, after Henan's economic development model was adjusted through the expansion of long-term consumption demand, the investment rate began to slow down and the final consumption rate gradually increased. However, the proportion of Henan's residential consumption in the GDP has been greatly reduced since 2003, and has only recently begun to show a slow pace of growth. Therefore, it can be predicted that the consumption inhibition effect in Henan will remain positive for CO_2 emissions for some time to come.

[6] The rise of Central China began in 2004 through the implementation of a national policy to promote six central Chinese provinces (Shanxi, Anhui, Jiangxi, Henan, Hubei, and Hunan), with the aim of constructing a national, unified market and promoting coordinated development between East and West China.

3.2.4 The population urbanization effect and regional development models

The results of the decomposition analysis for population urbanization effects at national and provincial levels are strikingly different. Figure 3f shows that the population urbanization effect was negative in 11 provinces, most of which are concentrated in the south, and especially in the Yangtze River Delta. One of these provinces, Jiangsu, is an important Chinese province in terms of its advanced economy and urbanization process. In 2018, Jiangsu ranked fifth in the entire country for its urbanization rate, and second for its GDP. Shanxi, by comparison, is an important base for coal production that ranked 24th for its GDP and 16th for its urbanization rate in 2018. Evidently, there is a wide gap between these two provinces that relates to differences in the degrees of their economic development and their urbanization rates. Therefore, we chose these two provinces as case studies for analyzing the population urbanization effect.

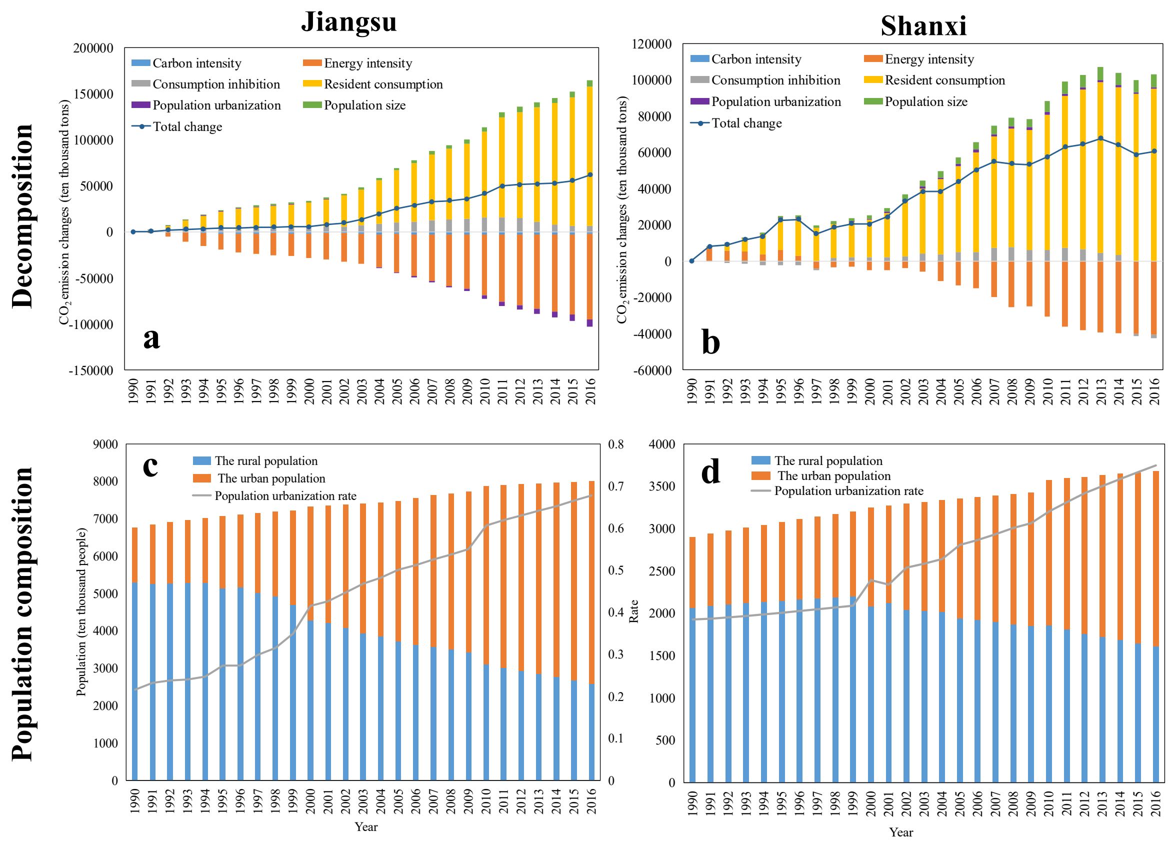


Figure 6. Decomposition results for Jiangsu and Shanxi (a and b) and their population composition (c and d).

Figures 6a and b show the respective decomposition results for Jiangsu and Shanxi. As noted in section 3.2.1, the trends for population urbanization and consumption inhibition effects were similar, with both exhibiting inverse U-shapes. However, this trend was clearly discernable for Jiangsu but not for Shanxi. During the period 1990–1999, the positive population urbanization effect in Jiangsu increased continuously (Fig. 6a). Since 2000, this positive effect has decreased, eventually becoming negative in 2004. However, the population urbanization effect has always been positive in Shanxi (Fig. 6b). From 1990 to 2006, this positive effect increased. The year 2007 constitutes a line of demarcation when the positive effect began to decrease. The change trend regarding this effect in these two provinces also assumed an inverse U-shape.

During the period 1990–2000, the positive effect of population urbanization in Jiangsu continuously increased in line with the acceleration of the urbanization process in this province. The development and opening up of the Shanghai Pudong area, which began in 1990, has provided an opportunity for the overall development of Jiangsu's export-oriented economy, and a number of development zones have emerged in the southern part of the province. The construction of a development zone and the pursuit of export-oriented economic development have been the main drivers of Jiangsu’s urbanization process. The urban population rate increased from 23.2% in 1991 to 27.3% in 1995 (Fig. 6d). From 1996 to 2000, Jiangsu’s government increased its investments in transportation and energy development in the northern part of the province. Moreover, it greatly improved the infrastructure and investment environment and promoted urbanization throughout the province [65]. From 1996 to 2000, the number of big cities with populations above 500,000 increased from 9 to 12, with an increase of 1.35 million urban population (i.e., 54.3% of the increase in urban population). During the same period, the level of urbanization increased at a fast pace from 27.3% in 1996 to 41.5% in 2000. Subsequently, Jiangsu entered a phase of rapid development entailing optimization and improvement in the quality of the industrial structure [65]. The provincial government adjusted the administrative boundary to expand the cities’ development spaces. During the period of the 11th Five-Year Plan, it further modified the industrial structure and developed high-tech industry to provide a new impetus for the advancement of urbanization. Since 2000, as a result of the adjustments made to the mode of urbanization, the positive effect of population urbanization on CO_2 emissions in Jiangsu gradually decreased and was eventually transformed into a negative effect in 2004.

By contrast, Shanxi’s urbanization process has been relatively slow (Fig. 6d). With the onset of initiatives to develop China’s market economy at the end of the 20th century, following the introduction of the reform and opening-up process, the urban population flow became conspicuous. The slow process of urbanization can be attributed to the reduction in coal prices during the period 1990–1999, which led to significant decreases in the populations of coal-dominated cities [66]. Therefore, the positive effect of population urbanization increased slowly during this period. In the early 21st century, with the gradual introduction of a market economy, the role of the market in the allocation of labor resources was strengthened [67]. Following the implementation of the Rise of Central China policy, a large influx of labor has flooded these cities, accelerating the population urbanization process. Consequently, the positive population urbanization effect increased from 2000 to 2007, subsequently reflecting a smooth change process with a small reduction from 2007 to 2011. This is because Shanxi entered a stagnant phase of economic development, entailing long-term reliance on natural resources and energy. Industrialization in the province, though ahead of urbanization, is excessively dependent on the mining industry. However, the ability of the mining industry to absorb labor is far lower than that of the manufacturing sector, resulting in a relatively low number of employees. In 2012, the ratio of the manufacturing industry's added value to that of the entire industry of the province was only 31.7%, whereas that of the mining industry was 63.4% [55]. Insufficient development of the manufacturing industry and the weak ability of this industry to absorb labor have hindered Shanxi's urbanization process. After 2012, the positive effect of population urbanization declined significantly. The likely reason is that since the period of the 11th Five-Year Plan, Shanxi's government has been adjusting its industrial structure, actively guiding the development of secondary and tertiary industries and changing the original economic structure focusing on a single industry. At the same time, the quality of urbanization has improved.

3.2.5 Changes in the six factors from the perspective of urbanization

In the previous discussions, we elucidated the differential impacts of six key drivers of China's CO_2 emissions by factor and province. Table 4 presents a summary of the impacts of changes relating to three broad categories (Fig. 1) that sheds further light on the effects of these drivers in the different provinces between 1990 and 2016. These categories are energy (carbon intensity and energy intensity), consumption (consumption inhibition and residential consumption), and population (population urbanization and population size).

Table 4 Contributions of energy, consumption, and population to energy-related CO_2 emissions in 2016 (relative to 1990)

No.	Province	(a) Energy				(b) Consumption				(c) Population			
		Carbon intensity effect		Energy intensity effect		Consumption inhibition effect		Resident consumption effect		Population urbanization effect		Population size effect	
		Emissions	Rank	Emissions	Rank	Emissions	Rank	Emissions	Rank	Emissions	Rank	Emissions	Rank
1	Heilongjiang	-587.9	12	-48,143.9	25	1,845.6	20	60,517.0	10	1,166.8	8	1,479.2	23
2	Jilin	1,033.9	5	-33,240.6	14	9,198.1	4	32,326.9	20	750.2	9	984.9	27
3	Liaoning	-701.4	13	-101,650.7	29	-4,480.6	30	141,201.0	4	3,132.4	1	4,942.6	12
4	Hebei	-1,523.8	18	-78,543.4	27	9,629.3	3	124,351.6	3	-757.6	24	7,596.5	4
5	Beijing	-2,047.6	23	-34,107.7	16	-2,750.8	29	37,146.4	19	-878.6	26	7,167.5	5
6	Tianjin	2,050.0	3	-23,604.7	11	1,452.7	21	27,946.9	24	1,571.0	5	5,062.5	11
7	Shandong	-1,574.5	20	-103,448.1	30	926.3	23	171,204.6	1	1,692.5	4	7,836.1	3
8	Jiangsu	-1,733.8	22	-92,936.3	28	6,718.9	11	151,075.1	2	-7,965.0	30	6,565.0	9
9	Shanghai	-1,705.5	21	-35,016.9	17	-2,267.4	28	47,881.7	16	172.1	14	9,098.3	2
10	Zhejiang	-6,254.8	29	-38,129.2	18	7,249.3	8	70,185.1	9	-5,574.3	29	5,424.0	10
11	Fujian	-1,559.0	19	-18,085.3	7	5,298.9	13	30,503.2	23	671.0	11	2,363.7	16
12	Guangdong	-5,866.9	28	-44,909.1	24	6,503.9	12	69,683.5	8	1,899.2	3	13,125.9	1
13	Guangxi	-1,217.9	16	-12,804.7	5	3,180.0	17	24,401.5	26	-43.2	19	1,013.2	26
14	Hainan	171.0	7	-1,299.0	1	253.0	26	4,087.7	30	67.3	18	428.9	30
15	Inner Mongolia	8,766.0	1	-33,699.0	15	9,669.0	2	56,732.2	11	87.7	17	2,599.2	14
16	Shanxi	-415.0	10	-40,100.0	20	-2,095.6	27	95,266.9	6	736.0	10	7,082.5	7
17	Henan	-2,383.9	24	-69,261.1	26	7,314.9	7	100,231.9	5	331.2	13	6,720.8	8
18	Anhui	-3,123.1	25	-43,499.8	23	8,064.2	6	72,771.5	7	-2,052.2	27	1,967.6	21
19	Jiangxi	-1,004.2	15	-20,475.9	8	3,785.0	15	32,111.5	21	-688.8	23	1,835.7	22
20	Hubei	-73.9	9	-40,531.7	22	7,185.0	9	59,445.7	12	-2,353.9	28	2,482.8	15
21	Hunan	-5,493.7	27	-40,451.6	21	8,606.8	5	58,189.2	13	-793.6	25	2,003.2	20
22	Shaanxi	-50.4	8	-32,635.8	13	9,701.1	1	46,905.9	17	-530.1	22	2,097.4	17
23	Chongqing	-990.4	14	-10,309.5	4	2,477.6	18	19,527.0	27	1,500.6	6	540.3	29
24	Guizhou	862.7	6	-28,062.5	12	3,180.4	16	43,690.8	18	-324.4	21	1,053.7	25
25	Ningxia	1,993.0	4	-9,891.3	3	777.7	25	18,221.8	28	475.2	12	2,054.1	19
26	Gansu	4,161.8	2	-21,690.5	9	1,194.0	22	29,969.9	22	1,259.8	7	1,465.9	24
27	Sichuan	-7,904.8	30	-38,263.7	19	6,838.9	10	57,160.5	14	2,384.5	2	2,812.6	13
28	Yunnan	-4,133.3	26	-15,157.3	6	2,134.3	19	25,785.1	25	-216.3	20	2,097.0	18
29	Qinghai	-416.5	11	-4,002.6	2	804.9	24	7,855.4	29	166.1	15	748.9	28
30	Xinjiang	-1,296.8	17	-22,250.9	10	4,993.6	14	44,131.7	15	141.6	16	7,148.1	6

Note: The blue-colored (red-colored) bars show increases (decreases) in CO_2 emissions

As shown in column (a) of Table 4, the effects of carbon intensity and energy intensity were the main drivers of emission reduction. These two effects are also closely related to the energy structure and technology in the urbanization process. An examination of the provinces with prominent carbon intensity effects reveals that their energy structures tend to be diversified and are not limited to a coal-centered structure (section 3.2.2). For example, in Sichuan and Yunnan, infrastructure related to hydropower and natural gas is developing rapidly, and Zhejiang has adjusted its power supply structure by developing photovoltaic, offshore wind, and nuclear power. Similarly, Hunan is actively reducing the proportion of its traditional energy sources and is developing clean energy. Energy technology has important effects on the urbanization process that relate not only to energy consumption and energy efficiency but also to environmental impacts. As shown in Table 4, the industrialized regions evidence a significant negative energy intensity effect. For example, the prominent energy intensity effects of Liaoning, Hebei, Shandong, and Jiangsu, which are key industrial centers, confirms the importance of energy technology in the urbanization process of industrial regions. Such technology determines industrial production and overall urban economic development.

The population size effect is indicative of the progress of urbanization. The progress of urbanization brings about an expansion in the scale of a city and a change in its population size. Highly urbanized regions, such as Beijing and Shanghai, generate more employment opportunities, which encourage population aggregation, and industrial regions, such as Guangdong and Shandong, can also absorb large numbers of workers. The population urbanization effect evidently depends on the degree of urbanization. An examination of the geographical distribution of population size effects reveals that most of the provinces evidencing a negative effect are concentrated in the economically developed Yangtze River Delta. The economic development model of each province has a direct impact on the population urbanization effect. Taking Jiangsu as an example of a province evidencing the greatest negative impact (section 3.2.4), the rate of tertiary industry's contribution to the GDP in 2017 was 56% while that of secondary industry was 42.4%, indicating successful industrial restructuring in relation to urbanization.

Among the six factors influencing changes in CO_2 emissions in China during the period 1990–2016, the residential consumption effect was the main driver. This finding indicates that rapid urbanization within China is associated with a significant increase in households' incomes and the overall strengthening of their consumption capacities. The positive effect is particularly apparent in developed urban areas, such as Beijing, Shanghai, and Jiangsu. The consumption inhibition effect reflects the transformation of the developmental mode of urbanization (see section 3.2.3). The distribution of its negative effect, shown in column (b) of Table 4, suggests two distinct reasons for this negative impact. The first reason relates to highly developed urbanization. Developed cities in China, such as Beijing and Shanghai, entered a stage of advanced urbanization from an early period. Their mode of economic development has changed from one that is production driven to one that emphasizes stimulating consumption and expanding domestic demand to achieve more sustainable urban development. The second reason relates to the transformation of the developmental mode of urbanization. Liaoning and Shanxi are typical examples of heavy industry bases built in the early period of China's developmental process. The slow progress of urbanization, which was concentrated in industrial areas, impeded the overall urbanization process. With the adoption of measures to balance regional development, improvements in social infrastructure, and the promotion of a consumptive environment, the consumption inhibition effect gradually changed into a negative impact in these two provinces.

4. Conclusion

We applied a LMDI approach using six key drivers to examine the impacts of urbanization on changes in CO_2 emissions across 30 Chinese provinces during the period 1990–2016. The main findings from our decomposition analysis are as follows.

1) The impacts of urbanization on CO_2 emissions in China, which evidenced distinct regional characteristics, gradually increased during the study period.
2) The energy intensity effect was the most important driver of reduced CO_2 emissions while the residential consumption effect was the main driver of increased CO_2 emissions in all of the provinces.
3) The rapid advance of urbanization in the 30 provinces has strengthened the purchasing power of households, promoting residential consumption, which has emerged as a vital new factor in the growth of CO_2 emissions.
4) Carbon intensity evidenced a relatively weak effect in the 30 provinces. Moreover, there were clear differences in this effect among the provinces. For example, in Sichuan and Yunnan, where hydropower accounts for a large proportion of the energy supply, carbon intensity exerted a strong negative effect.
5) A negative consumption inhibition effect was evident in some highly urbanized and industrialized provinces, such as Beijing and Shanxi. Similarly, the population urbanization effect was negative in some highly urbanized provinces, including Jiangsu and Shanghai. However, these two effects were always positive at the national level.

The following conclusions can be derived from these findings. The energy intensity effect, which is the most important driver of CO_2 emission reduction, is indicative of China's attention to technological innovation in production. At the same time, the residential consumption effect, a new vital driver of CO_2 emissions is increasing, which also indicates that the Chinese government's economic policies of expanding domestic demand and stimulating consumption have been effective in recent years. The fast progress of China' urbanization process has prompted rapid economic growth, resulting in increased incomes for households and the strengthening of their purchasing power, which has increased their consumption power. Moreover, residential consumption has further increased domestic demand and promoted economic growth. Consequently, urbanization has advanced further.

The regional characteristics of changes in CO_2 emissions in each province can be attributed to the urbanization of industrial areas (the four major industrial bases) and variations in regional resources. In general, the energy intensity effect has played a major role in restraining CO_2 emissions, which is aligned with the common goal of reducing energy intensity in the economic development processes of industrial provinces. Furthermore, the carbon intensity effect was found to be resource-dependent, with the types of resources in each region determining these effects.

These drivers of provincial CO_2 emissions demonstrate that the formulation of a national policy to reduce CO_2 emissions should account for different driving forces in different regions. Specifically, the results of the analysis suggest the following policy recommendations:

1) *Guiding residents in appropriate consumption:* The transformation of China's economic model has further strengthened residential consumption, which will promote economic development and further accelerate the urbanization process. With advancing urbanization, households' purchasing power has been continuously enhanced, inducing a positive effect of residential consumption. Therefore, the process of promoting urbanization should not only focus on advancing a consumption-driven economy; it should also seek to guide residents, inculcating within them the concept of an ecological civilization and consciousness of environmental responsibility to achieve the goal of CO_2 emission reduction. At the same time, the government needs to formulate an environmentally friendly consumption policy, promote the green consumption concept, and encourage residents to change their consumption patterns.
2) *Adjusting the energy structure*: Adjusting the energy structure is an important requirement of urbanization. At present, the energy intensity effect is the main driver of CO_2 emission reductions in most provinces, whereas the carbon intensity effect is relatively minor, evidencing significant regional differences. However, these findings indicate that there is scope for reducing CO_2 emissions in China by optimizing the energy structure in the future. Given the regional characteristics of China's CO_2 emissions, it is imperative to promote policies that improve energy structures by tailoring them to regional conditions, for example, by actively promoting policies for developing clean energy according to regional resource characteristics and reducing the consumption of fossil energy.
3) *Formulating carbon reduction policies in accordance with local conditions of urbanization:* Throughout this paper, we have drawn attention to the extensive impact of urbanization on

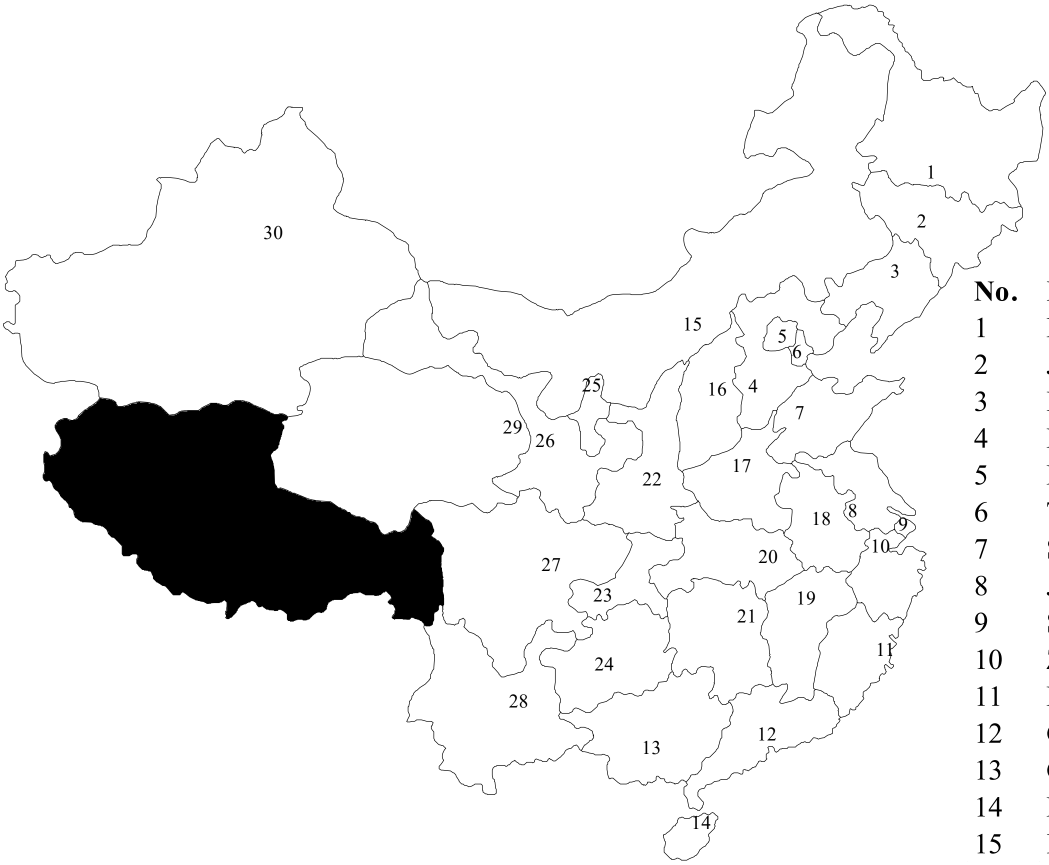
China's CO_2 emissions. However, it is important to consider its differentiated regional impacts. Therefore, strategies to reduce CO_2 emissions in the context of urbanization in China should be based on the actual situation in each province. The government needs to formulate carbon reduction policies in accordance with local conditions by considering the drivers of CO_2 emissions in light of each province's specific urbanization conditions. For instance, in the interior northwestern parts of China, including Inner Mongolia and Gansu, where coal accounts for a large proportion of energy supply, the development of energy technology should be promoted. More specifically, the governments of those provinces should implement energy policies that take advantage of the inland plateau terrain to develop clean forms of energy, such as wind and solar energy.

Last but not least, in addition to their implications for domestic policy formulation, the findings of this study also have important international implications. Because the next extensive phase of urbanization will occur in developing countries, these findings regarding the impacts of urbanization on changes in CO_2 emissions in the Chinese context can provide inputs for developing countries seeking to reduce their CO_2 emissions in the urbanization process. In the process of developing their economies and accelerating urbanization, developing countries should consider the impacts of urbanization on CO_2 emissions. This is because urbanization not only promotes residential consumption and stimulates domestic demand but it also increases CO_2 emissions caused by residential consumption. Orienting residents toward environment-friendly consumption is an important strategy that can contribute to the reduction of CO_2 emissions in future processes of urbanization in developing countries. At the same time, developing countries' carbon reduction policies under conditions of urbanization should conform to prevailing regional situations, accounting for their different characteristics, rather than being based solely on the overall characteristics of the country.

Acknowledgements

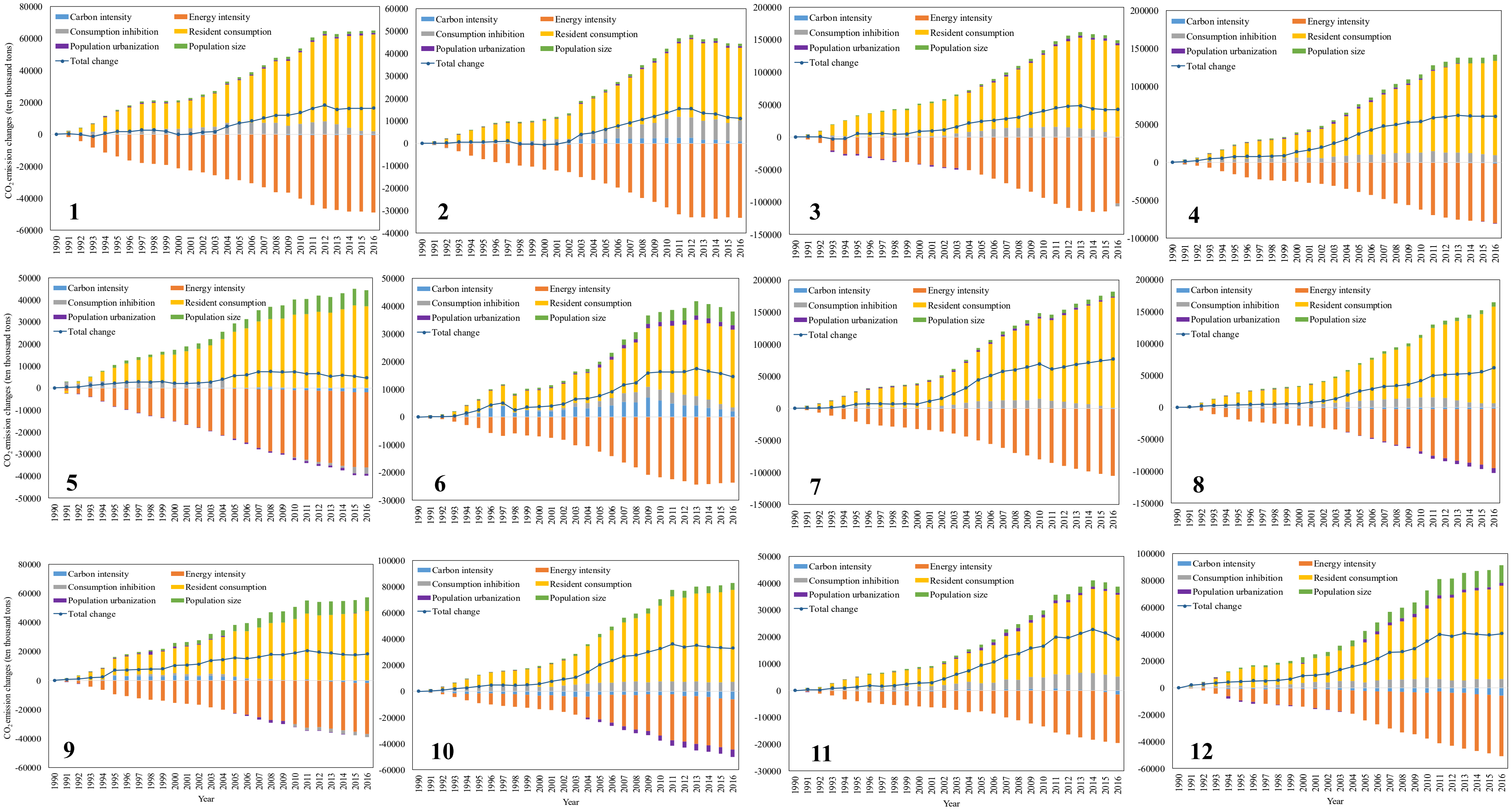
First and foremost, I would like to show my deepest gratitude to my supervisor, Prof. Ken'ichi Matsumoto, a respectable, responsible and resourceful scholar, who has provided me with valuable guidance in every stage of the writing of this thesis. Without his enlightening instruction, impressive kindness and patience, I could not have completed my thesis. His keen and vigorous academic observation enlightens me not only in this thesis but also in my future study. I would also like to thank all my teachers who have helped me to develop the fundamental and essential academic competence. I would also like to thank all the professors who helped me develop the fundamental and essential academic competence. I shall extend my thanks to Prof. Yosuke Shigetomi who gave me the inspiration for this research, and I also got a lot of support of thesis creation from my vice supervisor Prof. Yuki Yamamoto.

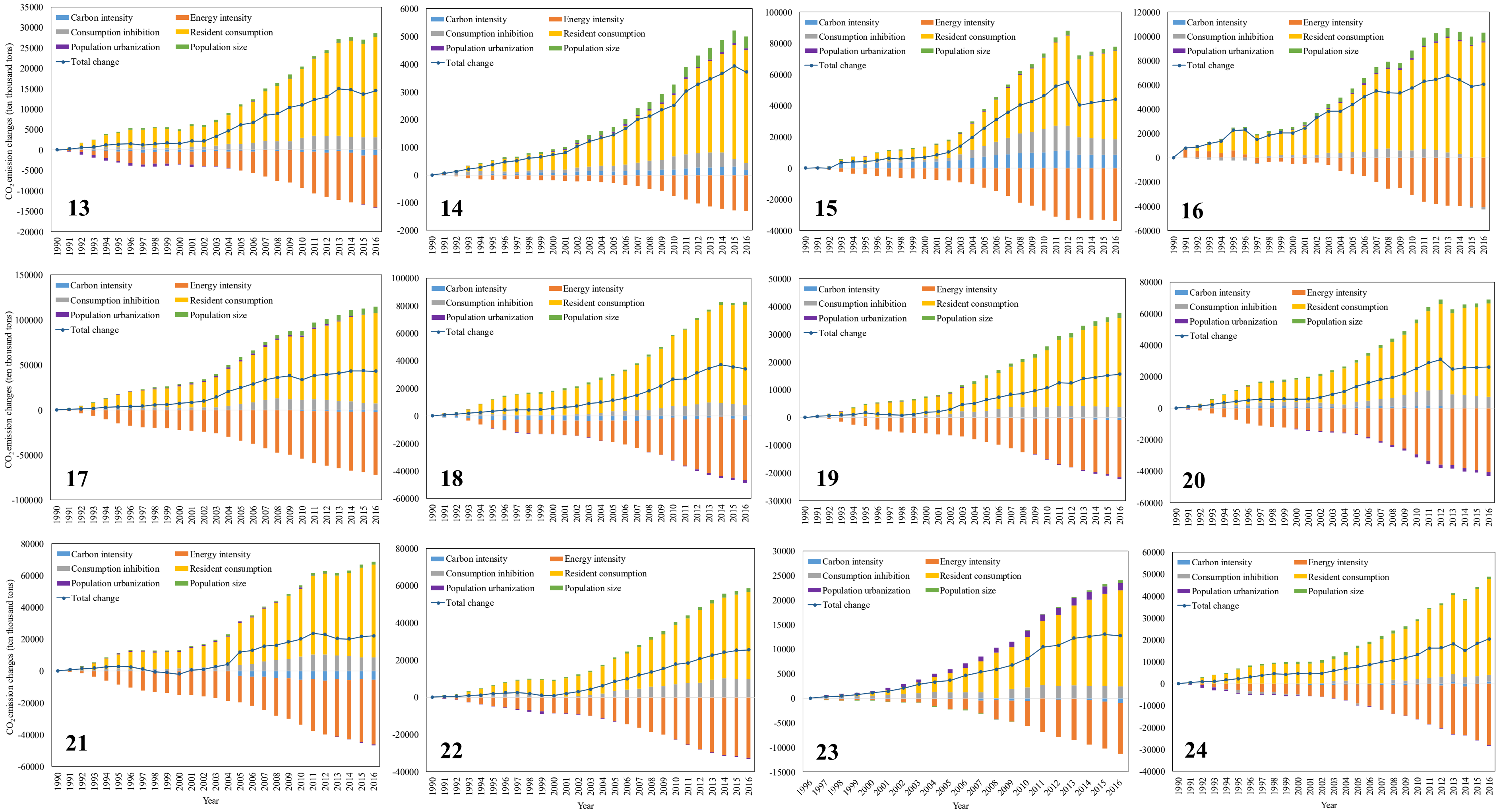
Appendix



No.	Province	No.	Province
1	Heilongjiang	16	Shanxi
2	Jilin	17	Henan
3	Liaoning	18	Anhui
4	Hebei	19	Jiangxi
5	Beijing	20	Hubei
6	Tianjin	21	Hunan
7	Shandong	22	Shaanxi
8	Jiangsu	23	Chongqing
9	Shanghai	24	Guizhou
10	Zhejiang	25	Ningxia
11	Fujian	26	Gansu
12	Guangdong	27	Sichuan
13	Guangxi	28	Yunnan
14	Hainan	29	Qinghai
15	Inner Mongolia	30	Xinjiang

Figure A 1. The geographical locations of Chinese provinces. The Tibet Autonomous Region, shaded black, was excluded from our study because of a lack of available data.


Carbon intensity
Energy intensity
Consumption inhibition
Resident consumption
Population urbanization
Population size
Total change
CO$_2$ emission changes (ten thousand tons)
Year
1
2
3
4
5
6
7
8
9
10
11
12



Carbon intensity
Energy intensity
Consumption inhibition
Resident consumption
Population urbanization
Population size
Total change
CO_2 emission changes (ten thousand tons)
Year
13
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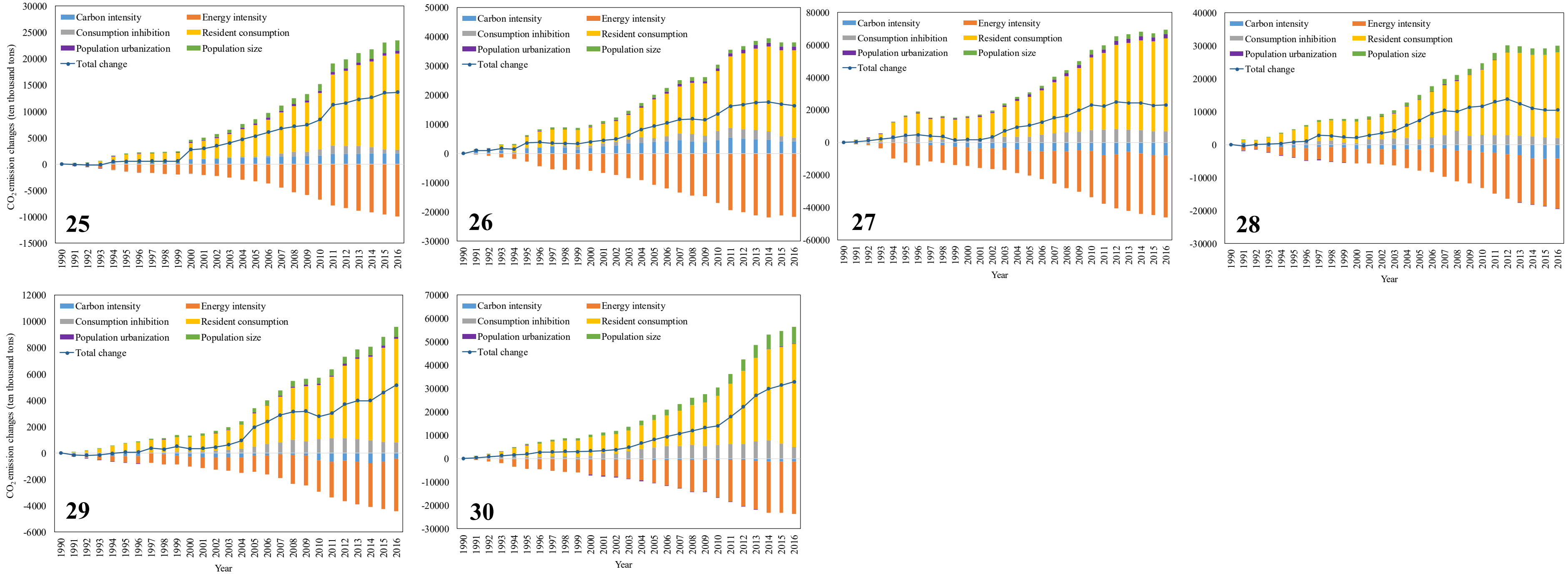

Figure A 2. Provincial-level decomposition results for all of the years of the study relative to 1990. The base year for Chongqing is 1996 because it became a directly administered municipality in 1997 and hence data became available around that year.

Table A1 Sources of provincial-level data.

No.	Province	URL
1	Heilongjiang	http://www.hlj.stats.gov.cn/tjsj/tjnj/
2	Jilin	http://tjj.jl.gov.cn/tjsj/
3	Liaoning	http://www.ln.stats.gov.cn/tjsj/sjcx/ndsj/
4	Hebei	http://tjj.hebei.gov.cn/hetj/tjsj/jjnj/
5	Beijing	http://tjj.beijing.gov.cn/tjsj/
6	Tianjin	http://stats.tj.gov.cn/Category_29/Index.aspx
7	Shandong	http://www.stats-sd.gov.cn/col/col6279/index.html
8	Jiangsu	http://tj.jiangsu.gov.cn/col/col4009/index.html
9	Shanghai	http://www.stats-sh.gov.cn/html/sjfb/tjnj/
10	Zhejiang	http://tjj.zj.gov.cn/col/col1525563/index.html
11	Fujian	http://tjj.fujian.gov.cn/xxgk/ndsj/
12	Guangdong	http://www.gdstats.gov.cn/tjsj/gdtjnj/
13	Guangxi	http://tjj.gxzf.gov.cn/tjsj/
14	Hainan	http://stats.hainan.gov.cn/tjsu/ndsj/
15	Inner Mongolia	http://tj.nmg.gov.cn/channel/nmg_tjj/col10471f.html
16	Shanxi	http://www.shanxi.gov.cn/sj/tjnj/
17	Henan	http://www.ha.stats.gov.cn/sitesources/hntj/page_pc/tjfw/tjcbw/tjnj/list1.html
18	Anhui	http://tjj.ah.gov.cn/tjjweb/web/tjnj_view.jsp?_index=1
19	Jiangxi	http://www.jxstj.gov.cn/id_tjnj201803120104397238/column.shtml
20	Hubei	http://tjj.hubei.gov.cn/info/iIndex.jsp?cat_id=10055
21	Hunan	http://tjj.hunan.gov.cn/tjsj/tjnj/
22	Shaanxi	http://tjj.shaanxi.gov.cn/site/1/html/126/127/233/list.htm
23	Chongqing	http://www.cqdata.gov.cn/publish.htm?code=A01
24	Guizhou	http://stjj.guizhou.gov.cn/tjsj_35719/sjcx_35720/gztjnj_40112/
25	Ningxia	http://nxdata.com.cn/publish.htm?cn=G01
26	Gansu	http://www.gstj.gov.cn/HdApp/HdBas/HdClsContentMain.asp?ClassId=70
27	Sichuan	http://tjj.sc.gov.cn/tjcbw/tjnj/
28	Yunnan	http://www.stats.yn.gov.cn/tjsj/tjnj/
29	Qinghai	http://www.qhtjj.gov.cn/tjData/qhtjnj/ http://tjj.hunan.gov.cn/tjsj/tjnj/
30	Xinjiang	http://www.xjtj.gov.cn/tjfw/tjsj/

Note: All data were taken from the official websites of provincial governments.

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