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ORIGINAL ARTICLE

Impacts of economic growth and urbanization on CO_2 emissions: regional differences in China based on panel estimation

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Abstract This study analyzed the impact of urbanization and the level of economic development on CO_2 emissions using the STIRPAT model and provincial panel data for China. This study classified the 29 provinces of China into three groups (eastern, central, and western regions) and examined regional differences in the environmental impacts of urbanization and economic development levels. The results demonstrated that there was an inverted U-shaped relationship between urbanization and CO_2 emissions in the central and western regions of China. However, we did not confirm the environmental Kuznets curve relationship between urbanization and CO_2 emissions in eastern China, where CO_2 emissions increase monotonically with urbanization. This study showed that the impacts of urbanization differ considerably. There was a U-shaped relationship between economic growth and CO_2 emissions. However, the point of inflexion was very low, which indicates that economic growth will promote CO_2 emissions in China. The share of the industry output value had a marginal incremental effect on CO_2 emissions. There was a decreasing effect of population scale on CO_2 emissions. Energy efficiency is the main factor that restrains CO_2 emissions, and the effect was higher in regions with low energy efficiency.

Keywords CO_2 emissions · Economic growth · Regional difference · Urbanization

Introduction

Since its economic opening and introduction of reform policies, and especially the implementation of the 11th Five-Year Plan (2006–2010), China's urbanization process has accelerated rapidly. The Chinese government has proposed a series of policies to promote the migration of peasant workers, which has led to significant increases in the urbanization levels. The urbanization rate will continue increasing by 1 % in each year of the next decade (Li and Yao 2009), and according to the planned development of China, China's urbanization ratio will reach 60 % by 2020 (China Urban Research Committee 2008). The rapid development of the economy and high-speed urbanization has caused the rapid growth of CO_2 emissions, and China has surpassed the USA as the largest contributor to energy

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consumption and global CO_2 emissions (Xu et al. 2014). In China, environmental problems have become increasingly serious and have seriously threatened the country's sustainable development plan (Song et al. 2013). Given the great pressure to reduce CO_2 emissions from the international community, China has proposed that by 2020, the CO_2 emissions per unit of GDP will have decreased by 40–45 % compared with 2005. Thus, what is the relationship between China's current urbanization process and CO_2 emissions? Is urbanization an important factor that has led to the rapid escalation of CO_2 emissions in China? Does an environmental Kuznets curve relationship exist between income and CO_2 emissions in China? Are there regional differences in the effects of urbanization on CO_2 emissions? In view of these issues, we will use panel estimation to conduct a regional analysis of the impacts of economic growth and urbanization on CO_2 emissions. This study will contribute to the development of CO_2 abatement policies in China.

Literature review

There is an extensive body of literature examining the relationship between energy consumption, CO_2 emissions, and urbanization at a national level. Some researchers have focused on the main driving forces of energy consumption and carbon emissions and detected positive relationships between urbanization, energy consumption, and carbon emissions (Parikh and Shukla 1995; York et al. 2003; Cole and Neumayer 2004; York 2007; Li and Yao 2009; Liddle and Lung 2010; Lin and Liu 2010). These links are attributable to low energy efficiency, low levels of energy-saving technology, and an absence of environmental awareness. Researchers following the other strand of studies have demonstrated the effects of urbanization on energy use and CO_2 emissions, and the results have indicated that increased public infrastructure efficiency (such as public transportation and other facilities) has reduced energy consumption and carbon emissions; therefore, urbanization has negative and significant effects on energy use and CO_2 emissions (Lariviere and Lafrance 1999; Shen et al. 2005; Fan et al. 2006; Pachauri and Jiang 2008; Dodman 2009; Liu 2009; Shobhakar 2009; Lin and Liu 2010; Gu et al. 2011; Liu et al. 2012; Sun et al. 2013). These two conflicting conclusions indicate the complex effects of urbanization on energy use and carbon emissions, which were due to the different methods and data used in these studies, the types of policies implemented in advance, or other factors that might counteract the effect of urbanization.

The impacts of urbanization on carbon emissions are affected by the economic development levels, industrial structure, technology, and other factors; therefore, urbanization has various effects on carbon emissions in different countries or regions. Zhang and Yan (2012) were the first to use the STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) model and provincial panel data from 1995 to 2010 for China to examine the effects of urbanization on CO_2 emissions from the perspective of regional differences in China. The results showed that the impact of urbanization on CO_2 emissions in the central region is greater than that in the eastern region. However, Zhang et al. paid no attention to the nonlinear relationships between urbanization and CO_2 emissions. Shi (2003) studied panel data with 93 countries during 1975–1996 and detected a direct relationship between population changes and CO_2 emissions, which varied with the level of affluence. Martinez-Zarzoso et al. (2007) found differences in the impact of population on emissions in old and new EU members. Poumanyvong and Kaneko (2010) studied the panel dataset of 99 countries over the period 1975–2005 and suggested that the impact of urbanization on energy use and emissions varies across the stages of development. Urbanization decreases energy use in the low-income group, whereas it increases energy use in the middle- and high-income groups. Martinez-Zarzoso and Maruotti (2011) analyzed the effects of urbanization on CO_2 emissions in developing countries during 1975–2003, and three groups of countries were identified where the impact of urbanization differed considerably, given the heterogeneity of the country samples. Some researchers have considered the existence of an inverted U-curve relationship between per capita pollution and urbanization (Ehrhardt-Martinez et al. 2002; Karen et al. 2002). Using ecological modernization theory as the theoretical basis, it has been argued that urbanization is a good proxy for modernization, so the environmental impact should decrease with higher proportions of urban population.

The main shortcomings of these investigations are that the results may be biased because of regional heterogeneity that stems from different regional regulations, or unmeasurable behaviors that affect energy use and CO_2 emissions. The omission of these unobserved variables will lead to inconsistent results that cannot be interpreted meaningfully (Brunnermeier and Levinson 2004). Only a few studies have explored the impact of urbanization on energy consumption or CO_2 emissions given heterogeneity in the samples from specific countries (Poumanyvong and Kaneko 2010; Zhang and Yan 2012). In addition, we found that some empirical studies included a squared term for urbanization in the STIRPAT model to test the existence of an environmental Kuznets curve between urbanization and CO_2 emissions (York et al. 2003; York 2007; Liu 2012), whereas few empirical studies have established nonlinear relationships between urbanization and CO_2 emissions in China while accounting for regional differences, even though there are some studies examining the environmental Kuznets curves between SO_2 emissions and economic growth (Cole et al. 1997; Matthieu and Andre 2009; He and Wang 2012). Therefore, to obtain insights into the regional differences in the nonlinear relationships between economic growth, urbanization, and CO_2 emissions in China, a further study of the impact of economic growth and urbanization on CO_2 emissions from a regional perspective based on panel data is still necessary.

Methodology and data

Dietz and Rosa (1997) decomposed the environmental impact (I) in a STIRPAT model using quantitative variables, that is, the population scale (P), affluence per capita (A), and technology (T). The model specification for a single year is given by the following equation:

$$I_i = \alpha P_i^{\beta} A_i^{\gamma} T_i^{\delta} e_i \tag{1}$$

In this model, α is a constant term, while β, γ, and δ are the elasticities of the environmental impacts for P, A, and T, respectively, which need to be estimated. e_i denotes the error term, and the subscript i is the province because this is a regional analysis. After taking the logarithm form, the model can be written as follows:

$$\ln(I_i) = z_0 + \beta \ln(P_i) + \gamma \ln(A_i) + \delta \ln(T_i) + z_i \tag{2}$$

where z_0, z_i denote the natural logarithm form of α and e_i in Eq. (1), respectively. β, γ, δ denote the percentage change in environmental impacts caused by 1 % changes in the driving factors (P_i, A_i, or T_i) given that other impact factors are constant. The model can be expanded to add other control variables to analyze their impacts on the environment, but the variables added should be consistent with the multiplication form designated in Eq. (2). The model has been applied in the analysis of the relationship between urbanization and economic changes, including energy consumption and CO_2 emissions (Fan et al. 2006; Lin et al. 2009; Wang et al. 2012). To investigate the impact of economic growth and urbanization on CO_2 emissions, the formula takes several variables into account because these variables may affect CO_2 emissions. The squared terms of the urbanization and income variables are introduced to examine the Kuznets curve relationship between income and the urbanization of China and CO_2 emissions. Therefore, we expanded the STIRPAT model as follows:

$$\begin{aligned} \ln CO_{2it} = {} & \beta_0 + \beta_1 (\ln Y_{it})^2 + \beta_2 \ln Y_{it} \\ & + \beta_3 (\ln URB_{it})^2 + \beta_4 \ln URB_{it} + \beta_5 \ln P_{it} \\ & + \beta_6 \ln E_{it} + \beta_7 \ln IND_{it} + u_{it} \end{aligned} \tag{3}$$

where CO_2 denotes the CO_2 emissions and represents the environmental impact (I); Y is the per capita GDP, which denotes income, represents the affluence per capita (A), and reflects the economic development level; URB denotes the urbanization level; P is the population scale. Technology (T) is measured by two variables (E and IND). E is measured as the GDP per unit energy consumption and is used to reflect the energy efficiency; IND denotes industrialization, which is measured as the proportion of the industry sector in the GDP and is used to reflect the industrialization development level. In Eqs. (1) and (2), the subscript is i, while in Eq. (3) it is "i, t" because they have information across time. The subscripts i and t denote the region and time.

Our regression estimation was conducted in two steps. First, we estimated the overall sample without any consideration for regional differences. Second, we classified the whole sample into three subsamples and examined the regional differences in the environmental impacts of urbanization and economic development levels. We classified the whole sample into the eastern region, the central region, and the western region (Table 1) to examine the geographic position and common features of economic development and urbanization levels for the provinces and municipalities of eastern, central, and western China. Data from the *China Statistical Yearbook, China Compendium of Statistics,* and *China Energy Statistical Yearbook* reveal that eastern China has the highest per capita GDP, followed by the central and western regions. Eastern China has the highest level of urbanization, followed by the central and western regions. From the perspective of industrial structure, eastern China has the highest output proportion (~40 %), followed by central China (35–40 %) and western China (30–35 %). Therefore, taking China's economic development and urbanization levels into account combined with the geographic position, we classified the whole sample into three subsamples. This classification based on regions is used frequently in China.

Table 1 Regional breakdown of provinces in China

Eastern region	Central region	Western region
Beijing	Helongjiang	Sichun
Tianjin	Henan	Guizhou
Hebei	Hubei	Shaanxi
Liaoning	Hunan	Gansu
Shanghai	Shanxi	Qinghai
Jiangsu	Jilin	Yunnan
Zhejiang	Anhui	Ningxia
Fujian	Jiangxi	Xinjiang
Guangdong	Inner Mongolia	
Shangdong		
Guangxi		
Hainan		

Table 2 Definition of the variables used in the study

Variable	Definition	Unit of measurement
CO_2 emissions (CO_2)	Energy-related CO_2 emission	10^4 ton
GDP per capita (Y)	GDP divided by the population at the end of the year	10^4 yuan per capita (1990 prices)
Population (P)	Total population at the end of the year	10^4
Urbanization (URB)	Percentage of the permanent residents living in cities	Percent
Energy efficiency (E)	GDP divided by total energy use	10^4 yuan per tce
Industrialization (IND)	The ratio of industry sector value added in GDP	Percent

Data for Tibet, Hongkong, Macao, and Taiwan were excluded. The data for Chongqing were included in Sichuan

Chongqing became a municipality in 1997. For continuity of the data, we classified Chongqing as being in Sichuan province. We did not collect data from Hong Kong, Macao, Tibet, and Taiwan province for the following reasons. First, data for these regions are not included in the *China Energy Statistics Yearbook* and *China Statistical Yearbook*. Second, although statistics for Hong Kong, Macao, and Taiwan province are an integral part of the overall national statistics, they are relatively independent from the mainland and have independent statistical data according to their own systems and legal provisions. Therefore, data for Hong Kong, Macao, and Taiwan province are not included in the *China Statistical Yearbook*. For these reasons, other relative studies generally have not used data for these areas. These data omissions are not material to the outcome of our analysis.

Given the integrity and availability of panel data, we included a balanced panel dataset from 29 provinces in China for 1995–2011. The data used in this study were obtained from the *China Statistical Yearbook* (1996–2012), *China Compendium of Statistics*, *China Energy Statistical Yearbook*, and the Statistical Yearbook of all provinces (1996–2012). Table 2 shows the definition of all of the variables. The data for the real GDP per capita of all provinces were calculated using a constant price ($1990 = 100$), and the unit was 10,000 (10^4) yuan. The unit for population was 10,000 (10^4). The units for the technological level, which were measured based on the energy efficiency and industrialization levels, were 10,000 (10^4) yuan per tce and percent, respectively. In addition, the total energy consumption data were collected from the *China Energy Statistical Yearbook*. The CO_2 emissions data were calculated according to the formula for CO_2 emissions given by the Intergovernmental Panel on Climate Change (IPCC) (2006) (http://www.ipcc-nggip.iges.or.jp/). The urbanization level was measured as the proportion of the permanent residents living in cities instead of the proportion of the non-agricultural population registered in the local hukou system. This measurement methodology was chosen for these reasons: First, the numbers recorded in the official Chinese statistics of the urban population (with non-agricultural hukou) are much lower than the actual population living in cities, particularly in large metropolitan areas such as Beijing, Shanghai, and Guangzhou, where a large number of immigrant workers are not registered in the local hukou system but are considered locals in their hometown/original villages. Second, the urban population in some regions, especially in eastern China, has been largely underestimated in the official statistics; this underestimation may be large enough to bias the model results if the proportion of the non-agricultural population is applied to measure the urbanization level.

Empirical analysis

The empirical studies conducted in this investigation were as follows. First, we tested the stability of the data, the results of which showed that all of the variables were integrated of order one, and a cointegration test was performed using the Kao method; the p value was below 0.001,[1] which showed that there was a long-term stable equilibrium relationship between $\ln CO_2$ and $\ln Y$, $\ln URB$, $\ln P$, $\ln E$, and $\ln IND$. Second, we tested for multicollinearity among the data of the non-quadratic terms using the variance inflation factor (VIF); the VIF values are all below 10, indicating that there is no multicollinearity. Third, we chose between fixed effects and random effects using the Hausman test, the results of which indicated that the p values of the Hausman tests are all below 0.005; therefore, we should use the fixed effects regression model. In the analysis of the whole country, we used the Driscoll-Kraay (DK) method because the overall sample belonged

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[1] The null hypothesis is that the cointegration relationship between the variables of the panel would not exist, and the alternative hypothesis is that the cointegration relationship between the variables would exist. The p value rejected the null hypothesis at the significant level of 1 %.

Table 3 Impacts of economic growth and urbanization on TCO_2

Variables	Overall sample	Eastern region		Central region	Western region
	Model (1) DK	Model (2) FGLS	Model (3) FGLS	Model (4) FGLS	Model (5) FGLS
ln*Y*	1.014***	0.979***	0.977***	1.01***	1.059***
	(0.009)	(0.008)	(0.007)	(0.004)	(0.014)
$(\ln Y)^2$	0.014***	0.013**	0.01**	0.005*	0.014***
	(0.002)	(0.005)	(0.003)	(0.002)	(0.004)
ln*URB*	0.226***	0.089	0.03***	0.151***	0.285*
	(0.057)	(0.014)	(0.009)	(0.044)	(0.131)
$(\ln URB)^2$	−0.033***	−0.008	–	−0.022***	−0.046*
	(0.008)	(0.0143)		(0.007)	(0.021)
ln*IND*	0.053*	0.112***	0.109***	0.01	−0.079**
	(0.022)	(0.022)	(0.021)	(0.007)	(0.028)
ln*P*	0.934***	0.905***	0.901***	1.049***	1.03***
	(0.009)	(0.026)	(0.025)	(0.017)	(0.034)
ln*E*	−1.004***	−0.97***	−0.97***	−1.015***	−1.06**
	(0.014)	(0.008)	(0.008)	(0.004)	(0.006)
constant	0.958261***	0.998*	1.134***	0.206	2.263***
	(0.142682)	(0.313)	(0.216)	(0.161)	(0.327)
Within-R^2	0.998300	–	–	–	–
Wald	–	926,902***	925,258***	801,909***	187,789***
Observations	493	204	204	153	136

Standard errors are shown in parentheses

*, **, *** denote statistical significance at the 5, 1, and 0.1 % level

to the wide panel dataset (section *N* was larger than the time *t*). In the analysis of the three regions, because the subsamples belonged to the long panel dataset (the time *t* was larger than the section *N*), we used the feasible generalized least squares (FGLS) regression and added a dummy variable to make it into a fixed effects model. In the model analysis, we also conducted the tests of within-group autocorrelation, cross-sectional correlation, and groupwise heteroscedasticity, and we made appropriate modifications in this study.

We performed a log regression analysis using the total CO_2 emissions (TCO_2) as the dependent variable, and the final results are shown in Table 3.

The regression results (Table 3) showed that either in the whole country or in different regions, the coefficients of the non-quadratic term and the squared term of income were positive, which indicates that there was a U-shaped relationship between economic growth and TCO_2. However, the point of inflexion was very low, which indicates that economic growth will promote TCO_2 in China. The relationship between urbanization and TCO_2 shows that the coefficient of the non-quadratic term of urbanization was positive, whereas that of the squared term was negative, which shows that there was an inverted U-shaped relationship between urbanization and TCO_2, where the point of inflexion was 30.5 % for the whole country, 30.9 % for the central region, and 22.1 % for the western region. The inverted U-shaped relationship demonstrates that increasing urbanization promotes TCO_2 below the point of inflexion, whereas increasing urbanization restrains TCO_2 when it passes the point of inflexion. In the eastern region, the coefficients of the non-quadratic term and the squared term of urbanization were not statistically significant at the $p < 0.05$ level, so we dropped the squared term and re-estimated the model, which made all of the variables significant at $p < 0.05$.[2] Therefore, there was an incremental linear relationship between urbanization and TCO_2 in the eastern region, the elasticity of which was 0.03, i.e., a 1 % increase in urbanization would lead to a 0.03 % increase in TCO_2. In terms of the relationship between industrialization and TCO_2, industrialization would promote TCO_2 for the whole country, and the elasticity was 0.052. For the eastern and central regions, industrialization would promote TCO_2, and their elasticities were 0.109 and 0.01, respectively. However, the elasticity of the central region was not statistically significant at $p < 0.05$. For the western region, industrialization would restrain TCO_2, and the

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[2] We have explored the Ramsey RESET test to be more convincing with the functional form. In the test, the null hypothesis is that the model has no omitted variables, and the *p* value was more than 0.05, which indicates the model has no omitted variables.

Table 4 Impacts of economic growth and urbanization on PCO_2

Variables	Overall sample	Eastern region		Central region	Western region
	Model (6) DK	Model (7) FGLS	Model (8) FGLS	Model (9) FGLS	Model (10) FGLS
ln*Y*	1.014***	0.979***	0.977***	1.01***	1.06***
	(0.009)	(0.008)	(0.007)	(0.004)	(0.014)
$(\ln Y)^2$	0.014***	0.013**	0.01***	0.005*	0.0136***
	(0.002)	(0.005)	(0.003)	(0.002)	(0.004)
ln*URB*	0.226***	0.089	0.03***	0.151***	0.285**
	(0.057)	(0.098)	(0.009)	(0.044)	(0.131)
$(\ln URB)^2$	−0.033***	−0.009	–	−0.022***	−0.046***
	(0.008)	(0.014)		(0.007)	(0.021)
ln*IND*	0.052**	0.112***	0.109***	0.01	−0.079**
	(0.022)	(0.022)	(0.021)	(0.007)	(0.028)
ln*P*	−0.066**	−0.095***	−0.099***	0.049**	0.03
	(0.009)	(0.025)	(0.025)	(0.017)	(0.037)
ln*E*	−1.005***	−0.97***	−0.97***	−1.015***	−1.06***
	(0.014)	(0.008)	(0.008)	(0.004)	(0.006)
constant	0.958***	0.998***	1.134***	0.206	2.263***
	(0.143)	(0.313)	(0.216)	(0.161)	(0.327)
Within-R^2	0.998	–	–	–	–
Wald	–	442,583***	441,797***	719,139***	114,427***
Observations	493	204	204	153	136

Standard errors are shown in parentheses

*, **, *** denote statistical significance at the 5, 1, and 0.1 % level

elasticity was −0.079, which means that industrialization will slightly curb TCO_2 in this region. Increased population will promote TCO_2, and its elasticity for the whole country was 0.934.[3] The elasticities of population scale relative to TCO_2 were 0.901, 1.049, and 1.03 for the eastern, central, and western regions, respectively. Increased energy efficiency will reduce TCO_2 substantially, and the elasticity for the whole country was −1.004. The elasticities for the eastern, central, and western regions were −0.97, −1.015, and −1.06, respectively.

We performed a log regression analysis using the per capita CO_2 emissions (PCO_2) as the dependent variable, and the results are shown in Table 4.

The results are very similar to Table 3. The main difference between Tables 4 and 3 is that the effects of population scale for the whole country and the eastern region on PCO_2 were negative, whereas the elasticity of PCO_2 relative to population scale for the central and western regions was positive. This was because population scale had two effects on PCO_2. First, population scale could increase the TCO_2, which would promote PCO_2. Second, given a specific amount of TCO_2, an increase in the population scale would reduce PCO_2. If the population scale can reduce PCO_2, we conclude that the restraining effect of population scale on PCO_2 would exceed the promoting effect. By contrast, if the population scale can promote PCO_2, we conclude that the promoting effect of population scale on PCO_2 would exceed the restraining effect.

We performed log regression analysis using the CO_2 emissions per unit of GDP (CO_2 emissions intensity, GCO_2) as the dependent variable, and the results, which are shown in Table 5, are very similar to Tables 3 and 4.

The main difference is that the coefficients of the non-quadratic term of income for the eastern region were negative, while the coefficients of the squared term of income were positive, which also indicates that there was a U-shaped relationship between economic growth and GCO_2. However, the point of inflexion was much higher, reaching 31,580 yuan (Index 1990). The current income in eastern China has not exceeded the point of inflexion; therefore, in eastern China, economic growth will restrain GCO_2, whereas economic growth will promote GCO_2, in other regions for the low point of inflexion. This was because economic growth had two effects on GCO_2. First, economic growth could increase the TCO_2, which would promote GCO_2. Second, given a specific amount of TCO_2,

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[3] The *F* value and *t* value are 284,801.04 and 99.86, respectively. Zhang and Yan (2012) also tested the elasticity for the whole country, and the result was 1.019, but in this study, they just paid attention to the linear relationships between urbanization, income, population, industry structure, and energy efficiency and CO_2 emissions.

Table 5 Impacts of economic growth and urbanization on GCO_2

Variables	Overall sample	Eastern region		Central region	Western region
	Model (11) DK	Model (12) FGLS	Model (13) FGLS	Model (14) FGLS	Model (15) FGLS
$\ln Y$	0.014	−0.021**	−0.023**	0.01*	0.059***
	(0.009)	(0.008)	(0.007)	(0.004)	(0.014)
$(\ln Y)^2$	0.015***	0.013*	0.01**	0.005*	0.014***
	(0.002)	(0.005)	(0.003)	(0.002)	(0.004)
$\ln URB$	0.226***	0.089	0.03***	0.151***	0.285**
	(0.057)	(0.052526)	(0.009)	(0.044)	(0.131)
$(\ln URB)^2$	−0.033***	−0.008	–	−0.022***	−0.046**
	(0.008)	(0.014)		(0.007)	(0.021)
$\ln IND$	0.052**	0.112***	0.109***	0.01	−0.079**
	(0.022)	(0.022)	(0.021)	(0.007)	(0.028)
$\ln P$	−0.066***	−0.095***	−0.099***	0.049**	0.03
	(0.009222)	(0.025)	(0.025)	(0.017)	(0.033)
$\ln E$	−1.005***	−0.97***	−0.97***	−1.015***	−1.06***
	(0.014)	(0.008)	(0.008)	(0.004)	(0.006)
constant	0.958***	0.998	1.134***	0.206	2.263***
	(0.143)	(0.313)	(0.216)	(0.161)	(0.327)
Within-R^2	0.995	–	–	–	–
Wald	–	201,861***	201,502***	289,128***	73,235***
Observations	493	204	204	153	136

Standard errors are shown in parentheses

*, **, *** denote statistical significance at the 5, 1, and 0.1 % level

economic growth would reduce GCO_2. If economic growth can reduce GCO_2, we conclude that the restraining effect of economic growth on GCO_2 would exceed the promoting effect. By contrast, if economic growth can promote GCO_2, we conclude that the promoting effect of economic growth on GCO_2 would exceed the restraining effect. Our analysis shows that, in the eastern region, the restraining effect of the economic growth on GCO_2 exceeded the promoting effect.

Results and discussion

The empirical analysis results reveal several interesting phenomena.

1. The relationship between urbanization and CO_2 emissions (TCO_2, PCO_2, and GCO_2) differed among regions. In particular, there was a linear incremental relationship between urbanization and CO_2 emissions in the eastern region. In the other regions, however, there was an inverted U-shaped relationship between urbanization and CO_2 emissions. The current level of urbanization in most regions has surpassed the point of inflexion, which means that urbanization will not promote CO_2 emissions in the central and western regions.

The process of urbanization involves not only a population transfer from the agriculture sector to non-agricultural sectors but it also involves the emergence of interregional migration. The eastern region is the most developed and has the highest standard of living, which attracts large outgoing migration from the western and central regions to the eastern region. Information from the National Bureau of Statistics of China shows that compared with the population in 2000, the proportion of the population in the eastern region in 2010 increased by 2.41 %, whereas the proportions in other regions declined. The large number of residents living in eastern region cities will promote the demand for energy-intensive products; therefore, CO_2 emissions will increase as a result of the large energy consumption in the eastern region. Urban expansion in the eastern region has fostered the development of metropolises and megalopolises. City sprawl in the eastern region always quickly accompanies improvements in public infrastructure, much of which is in the form of constructed facilities, such as road networks and electricity networks (Parikh and Shukla 1995), which also increases CO_2 emissions. Because of higher-income levels in the eastern region, the strong purchasing power can lead to a large demand for energy-consuming products, such as domestic appliances and private cars, which will promote carbon emissions. The eastern region has the highest urbanization level, which leads to the largest output value and the highest growth rate; this may cause an increase in energy consumption and carbon emissions each year. Although technological progress and energy efficiency promotion in the eastern region may reduce CO_2 emissions, the effects of increasing CO_2 emissions for the above reasons surpass those of reducing CO_2 emissions; therefore, a linear incremental relationship between urbanization and CO_2 emissions exists in the eastern region.

The inverted U-shaped relationship between urbanization and CO_2 emissions in the central and western regions can be explained as the ecological consequence of the industrial mix change: The upward part of the curve captures the relatively larger role of the industrial structure based on raw materials or dirty technology, which increases CO_2 emissions as the urbanization level rises; the downward part of the curve is evidence of industrial restructuring or adoption of clean technology, which mitigates CO_2 emissions as the urbanization level continues to grow (Qin and Wu 2014). Furthermore, in the process of urbanization, the proportion of the tertiary sector trends upwards. The continuously increasing proportion of the tertiary sector will, to a certain extent, restrict the growth of energy consumption and carbon emissions. The energy consumption of the industry sector is the main reason for energy consumption and carbon emission growth. Therefore, urbanization has different effects on energy consumption and carbon emissions at different urbanization levels because of the differing proportions of industrial and tertiary values. The proportions of industry in central and western regions showed little change, whereas, particularly in the later period, those for tertiary showed a significant upward trend. The proportions of tertiary, which reached 36.65 and 39.97 % in central and western regions, respectively, greatly surpassed the previous levels, which were only 29.6 and 32.5 %, respectively (see Electronic Supplementary Material). Therefore, in the later period, the process of urbanization will restrain CO_2 emissions. In addition, the process of urbanization in the central and western regions relies on relatively higher energy consumption in the first period, whereas it relies on relatively lower energy consumption in the later period (See Electronic Supplementary Material). In particular, with the progress of the West Development Project that was launched in 1999, commercial and transportation activities and the size of urban infrastructure have developed further, so in the western and central regions, excessive demand for high-energy products has led to rapid and sustained growth in energy consumption (Zhang and Yan 2012), which resulted in an increase in energy consumption and CO_2 emissions in the first period. However, with the enhancement of technological levels, consciousness of energy-saving and emission reduction, and upgrading of the economic structure, the process of urbanization would restrain CO_2 emissions.

2. In the whole country and in different regions, there was a U-shaped relationship between economic growth and CO_2 emissions.

CO_2 emissions decreased with economic growth during the first period for the following reasons. First, the Chinese government launched a series of energy-saving and emission reduction policies, including closure of energy- and emission-intensive enterprises and reorganization of the energy market (especially the coal market) in the mid-1990s (He and Zhang 2012). Second, constant improvements in industry energy efficiency in China led to a significant decrease in energy intensity and GCO_2 from 1995 to 2000 (Li and Wang 2008). Third, the outbreak of the East Asian financial crisis in 1997 led to lower investment, particularly in the next 3 years, and the decline in demand for energy, thereby reducing CO_2 emissions. The reasons why CO_2 emissions increased with economic growth thereafter perhaps lie in the fact that during 2001–2011, economic growth continued to play a dominant role in boosting production energy consumption growth, resulting in the growth of production energy consumption to 27,683.94 million tce annually, higher than in any other period (Wang 2014). The long-term rapid economic growth in China, which occurred at a rate of more than 10 % per year during 2003–2009, led to substantial increases in income, greater demand for energy products, and higher carbon emissions each year. This finding is supported by Chang (2010) and Sharma (2011). Maintaining fast and steady economic growth can lead to dramatic increases in CO_2 emissions. Our empirical results reveal that economic growth will promote TCO_2 and PCO_2 because China has passed the point of inflexion. Therefore, economic growth is the main factor driving CO_2 emissions. Our analysis also shows that, in eastern China, economic growth will restrain GCO_2 (economic growth will still promote TCO_2 and PCO_2 in the eastern region) because the current income level in eastern China has not passed the point of inflexion. This indicates that the restraining effect of the economic growth on GCO_2 exceeded the promoting effect, which is mainly due to the use of more advanced technology for energy-saving and emission reduction and to higher energy efficiency levels in the eastern region.

3. In terms of the effect of the share of the industry output value on CO_2 emissions, the eastern region had the maximum effect, followed by the central region, whereas the west region had the lowest effect.

Because industry accounts for the greatest proportion of energy consumption, a decrease in the proportion of industrial output directly restrains CO_2 emissions. At present, the share of the industry output value is highest in the eastern region ($\sim$ 40 %), followed by the central region

(35–40 %), and the lowest share is in the western region (30–35 %). The eastern region had the highest effect because it has the highest share of the industry output value. Therefore, China should try to control the share of the industry output value and encourage the development of the tertiary industry, especially in the eastern region. For the western region, industrialization would restrain CO_2 emissions (the elasticity was −0.0791). Over a long period, the western region has not been developed but it is rich in mineral resources, so the awareness of energy-saving and the management of emission reductions have improved in the western region as the industrialization level increased, which means that industrialization will slightly curb CO_2 emissions in this region.

4. Increased population will promote TCO_2, whereas it will reduce PCO_2 and GCO_2 in the eastern region. Population scale had a relatively lower impact on CO_2 emissions in the eastern region; the effects of population scale on CO_2 emissions were higher in the western and central regions.

Population scale led to an increase in TCO_2, which is mainly because increases in population lead to increased demand for energy consumption. The Chinese population scale has shown an increasing trend for a long time, which will inevitably lead to a greater demand for energy (Zhu et al. 2013). For example, the proportional energy consumption for residential use has increased by 19 and 9 % since 1996 in rural and urban areas, respectively (Fan et al. 2013). Residential energy consumption of both electricity and fuels is associated with the emission of many air pollutants. Qu and Jiang (2012) found that the elasticity of CO_2 emissions with respect to population scale is significantly close to unity. As the most economically developed regions are in eastern China, the standard of living there is the highest, so the consciousness of a low-carbon lifestyle is the highest. With enhancement of the consciousness of energy-saving and emission reduction, residents' lifestyles have changed, moving energy consumption trends toward even greater efficiency and emission reduction (Zhang and Yan 2012). This is because the relatively higher income and the higher awareness of CO_2 emissions reductions in the eastern region reduced the impact of population scale on CO_2 emissions (the elasticity of population scale relative to CO_2 emissions for the eastern region was the smallest). Our empirical analysis reveals that an increased population will reduce PCO_2 and GCO_2 for the eastern region because the restraining effect of population scale on PCO_2 would exceed the promoting effect. However, the similar standard of living in the central and western regions meant that there was less difference in the effect of population scale on CO_2 emissions in the central and western regions.

5. Energy efficiency is the main inhibiting factor for Chinese carbon emissions, and the effect of energy efficiency on CO_2 emissions was highest in the western region, followed by the central region, while the eastern region had the lowest influence.

Theoretically, if other factors remain unchanged, an improvement in energy efficiency generally results from technological progress, which restrains CO_2 emissions. Xu et al. (2014) revealed that industrial energy intensity in China determines the energy efficiency effect on carbon emissions. The eastern region had the highest energy efficiency, followed by the central region, while the western region has the lowest energy efficiency, which shows that the elasticity of CO_2 emissions relative to energy efficiency was negatively correlated with energy efficiency. This is probably attributable to the law of diminishing marginal production. Therefore, the western region should make the greatest efforts to improve the energy efficiency to reduce CO_2 emissions, followed by the central region and the eastern region.

Conclusions and policy implications

The primary objective of this study was to examine the nonlinear relationship between urbanization and CO_2 emissions from the perspective of regional differences. Urbanization has different effects on carbon emissions in separate regions because of differences in the economic structure, energy efficiency, technological levels, and life styles that occur in the process of urbanization. Although there have been many analyses of the effects of urbanization on emissions, this study contributes to the body of knowledge in this area, especially in terms of regional differences in the environmental Kuznets curve between urbanization and CO_2 emissions in China.

1. Our analysis revealed that the environmental Kuznets curve between urbanization and CO_2 emissions was identified in western and central China but was not observed in eastern China. In particular, there was a linear incremental relationship between urbanization and CO_2 emissions in eastern region. At present, the urbanization level of most cities in the central and western regions of China has surpassed the point of inflexion, which means that urbanization will not promote CO_2 emissions in these regions. Therefore, China should properly control the urbanization level of the eastern region and should promote the development of urbanization levels in the central and western regions to narrow the regional gap in the process of urbanization. This means that China's leadership made an extremely wise decision in developing the "go

west" policy in its 12th Five-Year Plan (2011–2015) for building a low-carbon society as the current urbanization, and carbon elasticity is found to be negative for central and western China. Furthermore, China should endeavor to construct low-carbon cities. The ecological urban development concept should provide guidelines to consider the coordinated development between humans and nature.

2. For the whole country and different region, there was a U-shaped relationship between economic growth and CO_2 emissions, but the point of inflexion was very low, which shows that economic growth will promote CO_2 emissions. Thus, the Chinese government should transform the mode of economic development and consider quantitative growth and quality improvement during economic development to transform from an extensive growth economy to an intensive growth economy. A moderate economic growth rate and high efficiency in reducing energy consumption and emissions are better choices for China.
3. The share of the industry output value had a marginal incremental effect on CO_2 emissions. Therefore, China should optimize the industrial structure by developing high technology and modern service industries, as well as vigorously developing the tertiary sector. In particular, it is necessary to reduce the share of high-energy-consumption industries and make great efforts to transform and upgrade the industrial structure.
4. Increasing income probably improves the energy-saving and emission reduction awareness of consumers, and there will be a decreasing effect of population scale on CO_2 emissions. Therefore, we should increase the awareness of residential energy-saving and emission reductions and advocate low-carbon lifestyles, especially in the cities of the central and western regions.
5. Energy efficiency is the main factor that restrains CO_2 emissions, and the effect was higher in regions with low energy efficiency. Thus, we should continue to improve energy efficiency in China, and there is room for this improvement (Wang et al. 2012). It is more necessary to improve the energy efficiency in the central and western regions because the effect would be greater in these areas (the effect was higher in the central and western regions). Energy efficiency derives mainly from technological progress, so we should increase the level of investment in advanced energy-saving technology and encourage research and development, especially in those areas where inducing advanced energy-saving technology is more effective, and the implementation of new technology is less costly.

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