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Urbanization, economic growth, and carbon dioxide emissions in China:

A panel cointegration and causality analysis

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Abstract: Elucidating the complex mechanism between urbanization, economic growth, carbon dioxide emissions is fundamental necessary to inform effective strategies on energy saving and emission reduction in China. Based on a balanced panel data of 31 provinces in China over the period 1997–2010, this study empirically examines the relationships among urbanization, economic growth and carbon dioxide (CO_2) emissions at the national and regional levels using panel cointegration and vector error correction model and Granger causality tests. Results showed that urbanization, economic growth and CO_2 emissions are integrated of order one. Urbanization contributes to economic growth, both of which increase CO_2 emissions in China and its eastern, central and western regions. The impact of urbanization on CO_2 emissions in the western region was larger than that in the eastern and central regions. But economic growth had a larger impact on CO_2 emissions in the eastern region than that in the central and western regions. Panel causality analysis revealed a bidirectional long-run causal relationship among urbanization, economic growth and CO_2 emissions, indicating that in the long run, urbanization does have a causal effect on economic growth in China, both of which have causal effect on CO_2 emissions. At the regional level, we also found a bidirectional long-run causality between land urbanization and economic growth in eastern and central China. These results demonstrated that it might be difficult for China to pursue carbon emissions reduction policy and to control urban expansion without impeding economic growth in the long run. In the short-run, we observed a unidirectional causation running from land urbanization to CO_2 emissions and from economic growth to CO_2 emissions in the eastern and central regions. Further investigations revealed an inverted N-shaped relationship between CO_2 emissions and economic growth in China, not supporting the environmental Kuznets curve (EKC) hypothesis. Our empirical findings have an important reference value for policy-makers in formulating effective energy saving and emission reduction strategies for China.

Keywords: urbanization; economic growth; CO_2 emissions; panel cointegration; Granger causality

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1 Introduction

Along with rapid economic growth, China has undergone an unprecedented process of urbanization since the 1978 economic reform (Liu and Yang, 2012; Long *et al*., 2013; Liu *et al*., 2015). China's urbanization rate has even developed far ahead of its economic growth since 2004 (Yang, 2013; Chen *et al*., 2013). Urbanization and economic development have long been regarded as interconnected processes. The rapid growth of China's extensive economy in recent decades has inevitably caused fast growth of CO_2 emissions. Furthermore, the construction of urban infrastructures and household consumption in the process of rapid urbanization has also led to an increase in CO_2 emissions (Peters *et al*., 2007; Raupach *et al*., 2007). Although urbanization has played a vital role in stimulating economic growth in China, it has created serious environmental problems, posing tremendous challenges to sustainable development (Liu and Diamond, 2005; Peters *et al*., 2007; Liu *et al*., 2008; Liu Yansui *et al*., 2014).

As the world's largest developing country, China is now facing the international restriction of reducing greenhouse gas emissions. The Chinese government set binding target in the "Twelfth Five-Year Plan" to reduce the unit GDP energy consumption and CO_2 emissions by 16% and 17% (down from 20% in the last plan) by the end of 2015, respectively. The government needs to explore new development paths to achieve the targets of energy saving and emission reduction while ensuring its economic development (Wang *et al*., 2011). Thus, the relationship between CO_2 emissions and economic growth is of particular research concern, especially China has promised to reduce its carbon emissions by 40%–50% in 2020.

Urbanization is closely linked to economic development, both of which inevitably increase energy consumption and CO_2 emissions (Zhang and Lin, 2012; Bai *et al*., 2014; Wang *et al*., 2014). Previous studies on urbanization-economy-environment nexus in China may be divided into three lines of research (Wang *et al*., 2011; Ma *et al*., 2011; Cheng *et al*., 2013; Sun *et al*., 2013; Liu *et al*., 2015; Zhou *et al*., 2015). The first strand of study has primarily focused on the relationship between economic growth and urbanization. Based on a positive correlation between economic growth and urbanization, some researchers argued that economic growth stimulates urban land expansion or vice versa. However, correlation does not imply causation (Bai *et al*., 2012). Some studies examined the causality between urbanization and economic growth. For instance, Li and Cheng (2006) uncovered that economic growth was the long-run Granger cause of China's urbanization. Wang *et al*. (2011) investigated the Granger causality between CO_2 emissions, energy consumption and economic output for China 28 provinces. Bai *et al*. (2012) examined the causal relationship between urbanization and economic growth in Chinese cities and provinces in recent decades and found that a long-run bidirectional causality exists between urbanization and economic growth. Recently, Chen *et al*. (2014) detected that the relationship between urbanization and economic development is similar to the Matthew effect in China. The second strand of study has largely discussed the driving forces behind the growth in CO_2 emission in China. Using the decomposition method, Zhang *et al*. (2009) identified economic activity was one of the driving forces influencing CO_2 emissions. A similar conclusion was obtained by Lin and Liu (2010). Feng *et al*. (2012) found that urbanization and associated income and lifestyle changes were important driving forces for the growth of CO_2 emissions in most parts of

China. Using an improved STIRPAT (stochastic impacts by regression on population, affluence and technology) model, Zhang and Lin (2012) argued that urbanization increases energy consumption and CO_2 emissions in China. At the local level, Wang *et al*. (2012a) found that urbanization was the main contributors to CO_2 emissions in Beijing, China.

The third strand of study has mainly concentrated on the relationship between economic growth and environmental quality with a particular focus on validation of the EKC hypothesis. Song *et al*. (2008) examined the relationship between three industrial pollutants (i.e., waste water, exhaust gases and solid waste) and economic growth in China based on the EKC hypothesis. Using the time series data of 1975–2005 in China, Jalil and Mahumd (2009) found the evidence supporting the EKC hypothesis for CO_2 emissions. Wang *et al*. (2011) observed the existence of a U-shaped curve between economic growth and CO_2 emissions. Most studies have confirmed the existence of a close relationship between economic growth and CO_2 emissions in China. However, some recent studies have observed mixed findings. For example, Wang *et al*. (2012a) argued that there was no evidence supporting the EKC hypothesis for CO_2 emissions in Beijing city, China. Using a panel data of 29 provinces in China from 1995 to 2009, Du *et al*. (2012) found that economic development was one of the most import factors affecting CO_2 emissions, but the EKC hypothesis was not strongly supported. So far, the existing findings on the relationship between economic growth and CO_2 emissions in China remain controversial.

Given urbanization may continue to be an important engine of China's economic growth, understanding the relationship between urbanization, economic growth and CO_2 emissions is essential for policymakers in formulating effective energy saving and emission reduction policies. Most of the existing studies only focus on the relationship between urbanization, economic growth and CO_2 emissions in China rather than on the linkages among those variables without consideration of regional differences as well. Thus, the relationships between urbanization, economic growth and CO_2 emissions in China still need further investigation. A main objective of this study was to investigate the relationship between urbanization, economic growth and CO_2 emissions at the national and regional levels using a balanced panel data of China's 31 provinces for the period 1997–2010. This is a period in China's history characterized by rapid economic development and a correspondingly large increase in urbanization rate and CO_2 emissions. In addition, China's road to urbanization has been thought of as unique for it is neither identical to the parallel-urbanization experience of developed countries nor does it duplicate the path of developing countries (Chen *et al*., 2012; Liu *et al*., 2013). Investigating the complex relationship between economic growth, urbanization and CO_2 emissions in China would provide a beneficial reference for other countries in formulating the energy saving and emission reduction strategies.

2 Data and methods

2.1 Data source

Urban population and built-up area are generally used as the proxy indicators of demographic urbanization (Bloom *et al*., 2008) and land (landscape) urbanization (Bai *et al*., 2012), respectively. We also chose built-up area (BA) and urban population (UP) as the proxy indices of land urbanization and demographic urbanization, respectively, and used real GDP per capita (pGDP) as economic indicator, and used CO_2 emissions as the environmental indicator (Table 1). All provincial data covering the period 1997–2010 are collected from the China Statistical Yearbooks (CSY) and China City Statistical Yearbook (CCSY). The CO_2 data over the period from 1997 to 2010 are obtained from the results calculated by Guan *et al*. (2012), in which the data on CO_2 emissions for all provinces are estimated from the publicly available energy statistics from Chinese authorities following the Intergovernmental Panel on Climate Change (IPCC) emission accounting approach. In the present study, all the variables are expressed in natural logarithms so that they may be considered elasticity of the relevant variables. The GDP is calculated at a constant price (1997 prices) and GDP per capita is calculated from GDP divided by the year-end population. The data for China do not include data for Hong Kong, Macao and Taiwan, China.

Table 1 Data description and sources

Indicators	Unit	Abbreviation	Meaning of indicators	Sources
Built-up area	km^2	BA	Land urbanization	CCSY
Urban population	persons	UP	Demographic urbanization	CSY
GDP per capita	yuan RMB	pGDP	Economic growth	CSY
CO_2 emissions	million tons	CO_2	Pollutant emissions	Guan *et al*., 2012

2.2 Econometric analysis

This study utilized panel unit root, cointegration and causality analysis to investigate the relationship between urbanization level, economic growth and CO_2 emissions. The empirical modeling framework in the present study consists of four stages. First, the presence of unit roots in the all variables was tested. The LLC and IPS methods were used to test the presence of the panel unit root (Levin *et al*., 2002; Im *et al*., 2003). In addition to these methods, Maddala and Wu (1999) and Choi (2001) provided two nonparametric unit root tests, the Fisher-ADF and the Fisher-PP statistics.

Second, because each of the variables contained a panel unit root, the heterogeneous panel cointegration test developed first by Pedroni (2004) was performed to examine whether there was a long-term equilibrium relationship between the variables. The Pedroni panel cointegration tests included two types, one was the panel cointegration test and the other was the group mean panel cointegration test. The former was based on the within dimension approach, which included the following statistics: Panel-*v*, Panel-*rho*, Panel-ADF and Panel-PP. The latter was based on the between dimension approach, which included three statistics: Group-*rho*, Group-PP and Group-ADF (Pedroni, 2004; Mahadevan and Asafu-Adjaye, 2007). It is generally accepted that the Panel-ADF and the Group-ADF statistics had better small sample properties than the other statistics, which made them more reliable.

Third, two techniques, i.e. the fully modified ordinary least squares (FMOLS) estimator and the dynamic ordinary least squares (DOLS) estimator were used to further estimate the long-run equilibrium relationships among the variables. The FMOLS estimator is believed to eliminate endogeneity in the regressor and serial correlation in the errors (Pedroni, 2000).

The DOLS estimators had a normal asymptotic distribution and their standard deviations provided a valid test for the statistical significance of the variables (McCoskey and Kao, 1999). In general, the DOLS technique is more reliable than the panel OLS estimation for panel data (McCoskey and Kao, 1999; Pedroni, 2000). The FMOLS estimator can be calculated in the following:

$$w_{i,t} = \alpha_i + \beta_i x_{i,t} + \sum_{k=-K_i}^{K_i} \gamma_{i,k} \Delta x_{i,t-k} + \varepsilon_{i,t} \quad (1)$$

where $w_{i,t}$ and $x_{i,t}$ are cointegrated with slope β_i, and β_i may or may not be homogeneous across i. $-K_i$ and K_i are leads and lags.

$$\hat{\beta}^*_{FMOLS} = \frac{1}{N}\sum_{i=1}^{N}\left[\left(\sum_{t=1}^{T}(x_{i,t}-\bar{x}_i)^2\right)^{-1}\left(\sum_{t=1}^{T}(x_{i,t}-\bar{x}_i)w^*_{i,t} - T\hat{\gamma}_i\right)\right]$$

$$w^*_{i,t} = w_{i,t} - \bar{w}_i - \frac{\hat{\Omega}_{2,1,i}}{\hat{\Omega}_{2,2,i}}\Delta x_{i,t} \text{ and } \hat{\gamma}_i = \hat{\Gamma}_{2,1,i} + \hat{\Omega}^0_{2,1,i} - \frac{\hat{\Omega}_{2,1,i}}{\hat{\Omega}_{2,2,i}}(\hat{\Gamma}_{2,2,i} + \hat{\Omega}^0_{2,2,i});$$

where $\xi_{i,t} = (\hat{\varepsilon}_{i,t}, \Delta x_{i,t})$ and $\Omega_{i,t} = \lim_{T\to\infty} E\left[\frac{1}{T}\left(\sum_{t=1}^{T}\xi_{i,t}\right)\left(\sum_{t=1}^{T}\xi_{i,t}\right)'\right]$ is the long-run covariance for this vector process which can be decomposed into $\Omega = \Omega_i^0 + \Gamma_i + \Gamma_i'$, where Ω_i^0 is the contemporaneous covariance and Γ_i is a weighted sum of auto-covariance.

The panel DOLS estimator is defined as:

$$\hat{\beta}^*_{DOLS} = \frac{1}{N}\sum_{i=1}^{N}\left[\left(\sum_{t=1}^{T} Z_{i,t} Z'_{i,t}\right)^{-1}\left(\sum_{t=1}^{T} Z_{i,t}\tilde{w}_{i,t}\right)\right] \quad (2)$$

where $z_{i,t} = [x_{i,t} - \bar{x}_i, \Delta x_{i,t-K_i}, \cdots, \Delta x_{i,t+K_i}]$ is vector of regressors, and $\tilde{w}_{i,t} = w_{i,t} - \bar{w}_i$.

Lastly, confirming the existence of cointegration between the variables, the next step was to examine both short- and long-run causality by performing Granger causality test based on vector correction model (VECM). The empirical models are specified as follows:

$$\Delta y_{i,t} = \theta_j + \sum_{k=1}^{K}\theta_{1k}\Delta y_{i,t-k} + \sum_{k=1}^{K}\theta_{2k}\Delta x_{i,t-k} + \mu\beta_{i,t-1} + \varepsilon_{i,t} \quad (3)$$

where Δ denotes the difference of the variable; K is the lag length; $\beta_{i,t-1}$ is the error correction term with lag 1; $\varepsilon_{i,t}$ is the residuals of the mode; μ is the coefficient of the error correction term $\beta_{i,t-1}$. The significance of causality results is determined by Wald F-test. In the short-run, the x does not Granger cause y where H_0: θ_{2k}=0 for all i and k, while the long-run causality can be established if μ=0.

Furthermore, we employed a heterogeneous panel Granger causality analysis, recently proposed by Dumitrescu and Hurlin (2012), to further verify the short-term Granger casual relationship between urbanization, economic growth and CO_2 emissions. The testing procedure is superior to former panel Granger causality tests since it can give efficient results even in panels with small sample sizes (Tugcu, 2014). The Dumitrescu and Hurlin (2012) test of Granger non-causality for heterogeneous panel is based on the stationary fixed-effects panel model:

$$y_{i,t} = \theta_i + \sum_{k=1}^{K} \beta_i^{(k)} y_{i,t-k} + \sum_{k=1}^{K} \delta_i^{(k)} x_{i,t-k} + \varepsilon_{i,t}\ ,\quad i = 1,2,....,N; t = 1,2,....,T \tag{4}$$

where x and y are two stationary variables observed for N provinces in T periods. $\beta_i^{(k)}$ denote the autoregressive parameters, and $\delta_i^{(k)}$ are the regression coefficient's slopes; $\delta_i=(\delta_i^{(1)},\ldots,\delta_i^{(k)})'$; individual effects θ_i are assumed to be fixed; K is the lag length. By definition, x causes y if and only if the past values of the variable x observed on the i-th province improves the forecasts of the variable y for this province i only. The test is based on the null hypothesis of homogeneous non-causality (*HNC*), there is no causal relationship from x to y for all the provinces of the panel $(\delta_i = (\delta_i^{(1)},...,\delta_i^{(K)})' = 0, \forall i = 1,..., N)$. Under the alternative hypothesis, there exists a causal relationship from x to y for at least one province of the sample. The test statistic is given by the cross-sectional average of individual Wald statistics defined for the Granger non-causality hypothesis for each province:

$$W_{N,T}^{HNC} = N^{-1} \sum_{i=1}^{N} W_{i,T}$$

where $W_{i,T}$ is the individual Wald statistic for the ith cross-section unit. Under the null hypothesis of non-causality, each individual Wald statistic converges to a chi-squared distribution with K degrees of freedom for $T \to \infty$.

The standardized test statistic $\tilde{Z}_{N,T}^{HNC}$ for fixed T samples is as follows (Dumitrescu and Hurlin (2002):

$$\tilde{Z}_{N,T}^{HNC} = \sqrt{\frac{N}{2K} \times \frac{T-2K-5}{T-K-3}} \times \left[\frac{T-2K-3}{T-2K-1} W_{N,T}^{HNC} - K \right] \to N(0,1) \tag{5}$$

2.3 The EKC model

According to the EKC hypothesis, the long-term relationship between economic growth and CO_2 emissions can be expressed as a logarithmic cubic function of the income (Grossman and Krueger, 1995). The simplified EKC model is given by:

$$\ln(\mathrm{CO}_2)_{it} = \alpha_0 + \beta_1 \ln(\mathrm{pGDP}_{it}) + \beta_2 \ln(\mathrm{pGDP}_{it})^2 + \beta_3 \ln(\mathrm{pGDP}_{it})^3 + \beta_4 \ln(\mathrm{BA}) + \varepsilon_{it} \tag{6}$$

where i-province (i=1, 2,…31), t-year (t=1, 2,…T); α_0 represents cross-section effect; ε_{it} is random disturbance; β_1, β_2, β_3 and β_4 are the estimated coefficients; pGDP is real GDP per capita; BA is built-up area. Eq. (6) allows us to test the various forms of environmental-economic linkages: $\beta_1>0$, $\beta_2<0$ and $\beta_3>0$ indicating an N-shaped relationship; $\beta_1<0$, $\beta_2>0$ and $\beta_3<0$ indicating an inverse N-shaped relationship; $\beta_1<0$, $\beta_2>0$ and $\beta_3=0$ indicating a U-shaped relationship $\beta_1>0$; $\beta_1>0$, $\beta_2<0$ and $\beta_3=0$ indicating an inverse U-shaped relationship, representing the EKC hypothesis, the turning point of the EKC is computed by $\omega=\exp(-0.5\beta_1/\beta_2)$; $\beta_1>0$, $\beta_2=0$ and $\beta_3=0$ indicating a monotonically increasing linear relationship; $\beta_1<0$, $\beta_2=0$ and $\beta_3=0$ indicating a monotonically decreasing linear relationship; $\beta_1=\beta_2=\beta_3=0$ indicating a level relationship.

3 China's urbanization, economic growth and CO_2 emissions

The variation in land urbanization, demographic urbanization, GDP and CO_2 emissions for China between 1997 and 2010 are shown in Figure 1. The number of China's inland cities had increased from 193 in 1978 to 657 in 2010, and its urban population increased from 172.45 million to 681.13 million with an annual average growth rate of 4.53% (NBSC, 2011; Figure 1a). According to the latest National New-type Urbanization Plan released by the central government, China's urbanization level was projected to reach 60% by 2020. Urban population growth in China was characterized by rural-to-urban migration (Gong *et al*., 2012). To accommodate this massive influx of population onto cities, China's urban area had expanded rapidly. Specifically, China's urban built-up area has increased from 13,685 km^2 in 1997 to 41,244 km^2 in 2010 (Figure 1b). During the same period, China's urban area had expanded by 201%, whereas the urban population had only increased by 105%, indicating that the rate of China's land urbanization is almost twice as fast as population urbanization. China's real GDP had rapidly increased from 7897 million RMB yuan in 1997 to 26,723 million yuan in 2010 with an average annual increase of 10.7% (Figure 1c). Large-scale industrialization and urbanization have also made China the largest CO_2 emitter in the world (Minx *et al*., 2011; IEA, 2012). The annual CO_2 emissions in China had been increasing from 2887 million tons in 1997 to 8175 million tons in 2010 (Figure 1d).

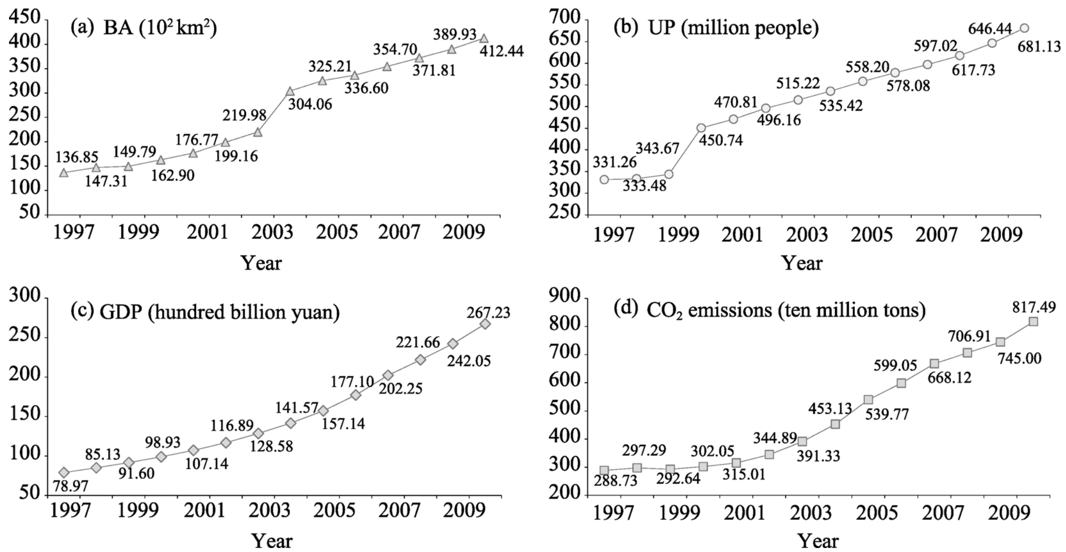

Figure 1 The changes in land urbanization (a), demographic urbanization (b), GDP (c) and CO_2 emissions (d) for China between 1997 and 2010

Linear regressions were further used to examine the changes in each variable for China's 31 provinces during the period 1997–2010. The slopes of the lines of best fit reflected the changes in the variables, and a greater slope indicated greater changes in the variables. Figure 2 displays the changes in urban population, built-up area, per capita GDP and CO_2 emissions for 31 provinces between 1997 and 2010. The top 5 provinces with the highest growth rate of urbanization population were Guangdong, Jiangsu, Shandong, Henan and Hebei (Figure 2a). In contrast, Tibet, Qinghai, Heilongjiang, Ningxia and Hainan were the provinces with the lowest growth rate of urban population. Similar to the urban population, the growth rate of built-up area in Guangdong Province was the highest, followed by Shandong, Jiangsu, Zhejiang and Henan (Figure 2b). The growth rate in GDP per capita in eastern China was relatively rapid over the past 14 years (Figure 2c). For CO_2 emissions, the growth rate in Shandong Province (53.25 million tons per year) was the highest, followed by Hebei (35.35 million tons per year), Inner Mongolia (31.45 million tons per year), Jiangsu (31.15 million tons per year) and Henan (28.54 million tons per year) (Figure 2d).

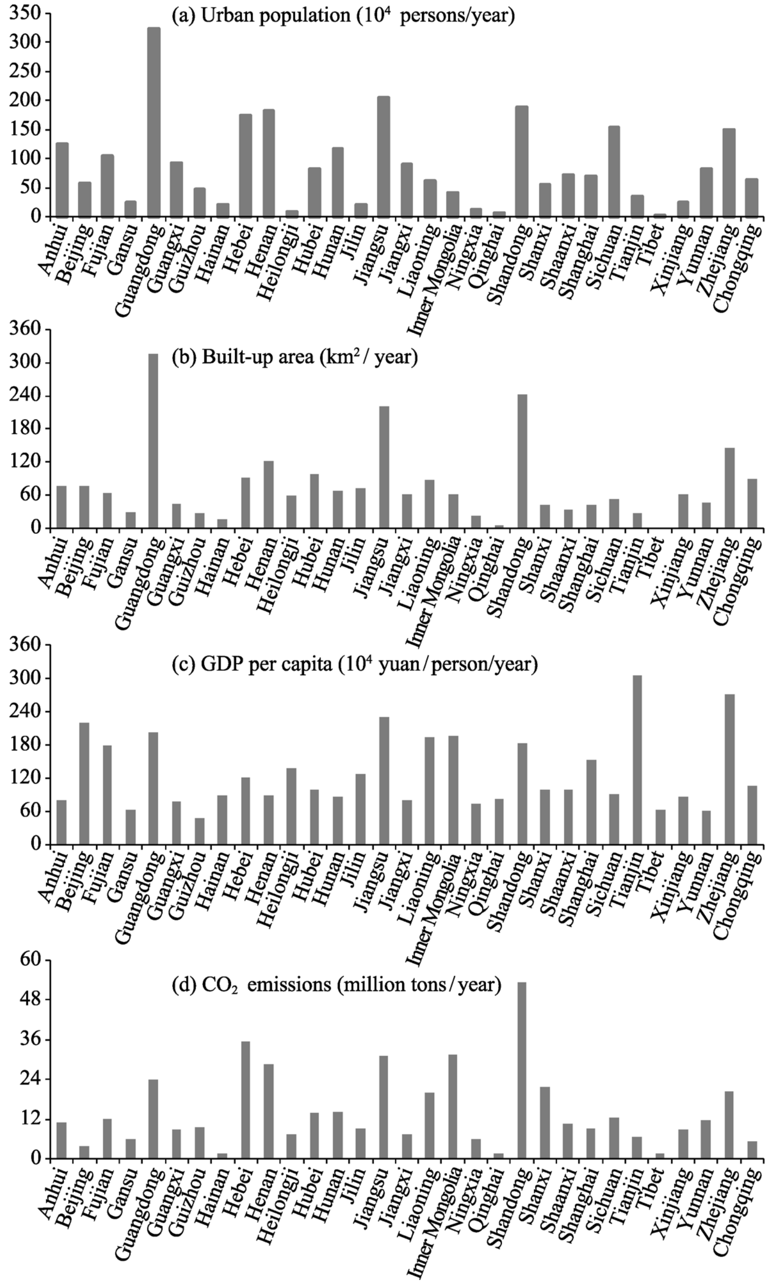

Figure 2 The growth rate in urban population (a), built-up area (b), GDP per capita (c) and CO_2 emissions (d) for China's 31 provinces

4 The relationships among urbanization, economic growth and CO_2 emissions in China

4.1 Panel unit root tests

It is advisable to check the presence of unit roots in the all variables before proceeding to any econometric analysis because using the conventional ordinary least squares (OLS) estimator with non-stationary variables might result in spurious regressions. Table 2 provides the panel unit root test results with and without a trend term. Results show that many variables are non-stationary in their levels, but most of them become stationary at the 5% significance level after taking first differences. This results indicate that built-up area, urban population, real GDP per capita, built-up area and CO_2 emissions in all panels were integrated at order one, suggesting a possible long-run cointegration relationship among these variables.

Table 2 Panel unit root test results

	Levels				
	Variable	LLC	IPS	Fisher-ADF	Fisher-PP
Intercept	BA	–2.75***	4.04	18.88	26.12
	UP	–4.68***	1.19	61.71	112.52***
	pGDP	5.863	12.1	9.23	4.24
	CO_2	1.65	7.18	8.4	6.45
Intercept and trend	BA	–1.50*	–1.47*	47.28	52.87
	UP	–9.11***	–0.27	67.02	27.63
	pGDP	–10.31***	–1.68**	91.47***	68.99
	CO_2	–6.39***	–2.32**	89.47**	74.63
	First differences				
	Variable	LLC	IPS	Fisher-ADF	Fisher-PP
Intercept	BA	–6.39***	–4.65***	115.01***	224.74***
	UP	–11.32***	–6.40***	149.70***	220.52***
	pGDP	–4.51***	–0.29	55.29**	52.95***
	CO_2	–6.12***	–4.11***	106.59***	195.71***
Intercept and trend	BA	–5.54***	–1.65***	75.35***	202.62***
	UP	–18.90***	–9.45***	203.53***	309.78***
	pGDP	–2.16***	0.42	59.99**	105.29***
	CO_2	–2.59***	0.10**	53.40**	158.00***

Note: Newey-West bandwidth selection using Bartlett kernel. Automation selection of lags was based on SIC. Levin, Lin and Chu test (LLC) Null: unit root (assumes a common unit root process); Im, Pesaran and Shin W-stat test (IPSW), ADF-Fisher Chi-square test (ADF) and PP-Fisher Chi-square test (PP) Null: Unit root (assumes an individual unit root process). BA, UP, pGDP and CO_2 are built-up area, urban population, and per capita GDP and CO_2 emissions, respectively. The null hypothesis of the LLC, IPS, Fisher-ADF and Fisher PP tests examines non-stationary. ***, ** and * indicates statistical significance at the 1%, 5% and 10% significance level, respectively.

4.2 Panel cointegration tests

If the series are integrated of the same order one can proceed with the cointegration test.

Table 3 presents the panel cointegration test results for all panel datasets. For Panel A, all seven panel cointegration tests rejected the null hypothesis of no cointegration at the 10% significance level except the Group *rho*-statistic, meaning a long-run equilibrium relationship between land urbanization and economic growth, which is in agreement with a previous study (Bai *et al*., 2012). For Panel B, most of the panel cointegration test statistics were statistically insignificant at the 5% level expect the Panel ADF and Group ADF, which indicates that no long-run stable relationship exists between demographic urbanization and economic growth. The Pedroni test results revealed the existence of cointegration between urbanization and CO_2 emissions only in Panel C, suggesting a long-run equilibrium relationship between land urbanization and CO_2 emissions. All the panel test statistics in Panel D were statistically insignificant at the 10% level, implying that no a long-run equilibrium linkage exists between demographic urbanization and economic growth. With the exception of the Group *rho*-statistics, the other six test statistics in Panel E reject the null hypothesis of no cointegration at the 5% significance level, suggesting a long-term cointegrating relationship between CO_2 emissions and economic growth. It can be concluded that constant long-run equilibrium relationship exists between land urbanization, economic growth and CO_2 emissions in China for the period 1997–2010.

Table 3 Panel cointegration test results

Statistics	Panel A	Panel B	Panel C	Panel D	Panel E
Panel *v*	1.51*	1.23	3.22***	–0.03	3.70***
Panel *rho*	–1.75**	0.10	–3.25***	0.71	–1.93**
Panel PP	–2.40***	–1.17	–7.18***	0.24	–5.31***
Panel ADF	–2.98***	–1.29*	–8.12***	–1.19	–8.10***
Group *rho*	1.48	2.77	–0.35	2.67	0.13
Group PP	–0.36*	0.97	–5.74***	0.96	–5.63***
Group ADF	–2.04**	–1.06*	–7.61***	–1.26	–8.80***

Note: Panel A (built-up area---pGDP); Panel B (urban population---pGDP); Panel C (built-up area---CO_2); Panel D (urban population---CO_2); Panel E (pGDP---CO_2). Statistics are asymptotically distributed as normal. All tests contain only the intercept and not the trend term. The variance ratio test is right-side, which the others are left-sided. The null hypothesis is that the variables are not cointegrated. Lag length selected based on AIC automatically with a max lag of 2. ***, ** and * reject the null of no cointegration at the 1%, 5% and 10% significance level, respectively.

4.3 Panel cointegration estimation

Once the cointegration relationship is established, the next step is to estimate the long-run parameters. Table 4 provides the results of the whole China and its three regions (i.e., eastern, central and western regions[1]) based on the panel FMOLS and DOLS estimations. The cointegration coefficients between urban population, pGDP and CO_2 emissions are not estimated since the lack of cointegration among them. Two estimators produced almost identical results, suggesting that the estimates were not sensitive to whether the FMOLS or the DOLS method was used. Often the values of the DOLS estimators are determined under the

[1] The eastern region includes Liaoning, Beijing, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Guangdong, Fujian and Hainan provinces; the central region includes Heilongjiang, Jilin, Shanxi, Henan, Anhui, Jiangxi, Hubei and Hunan provinces; and the western region includes Xinjiang, Gansu, Qinghai, Inner Mongolia, Ningxia, Shaanxi, Sichuan, Chongqing, Guizhou, Yunnan and Guangxi provinces (Zhong *et al*., 2011).

Table 4 Panel cointegration coefficients by FMOLS and DOLS for China and its eastern, central and western regions

Whole China							
Variable	Dependent variable: pGDP			Variable	Dependent variable: BA		
	DOLS (1,1)	DOLS (2,2)	FMOLS		DOLS (1,1)	DOLS (2,2)	FMOLS
BA	0.90*** (–27.29)	0.81*** (–21.66)	0.94*** (–27.58)	pGDP	0.66*** (–9.64)	0.22 (–0.47)	0.93*** (–43.33)
Variable	Dependent variable: CO_2			Variable	Dependent variable: CO_2		
	DOLS (1,1)	DOLS (2,2)	FMOLS		DOLS (1,1)	DOLS (2,2)	FMOLS
pGDP	0.83*** (–16.22)	0.60*** (–2.12)	0.94*** (–61.07)	BA	1.19*** (–36.78)	1.16*** (–29.56)	1.15*** (–34.88)
Obs	341	279	403	Obs	341	279	403
Eastern region							
Variable	Dependent variable: pGDP			Variable	Dependent variable: BA		
	DOLS (1,1)	DOLS (2,2)	FMOLS		DOLS (1,1)	DOLS (2,2)	FMOLS
BA	1.02*** (–50.73)	0.99*** (–6.63)	1.03*** (–38.21)	pGDP	0.66*** (–9.64)	0.43 (–0.51)	1.06*** (–26.07)
Variable	Dependent variable: CO_2			Variable	Dependent variable: CO_2		
	DOLS (1,1)	DOLS (2,2)	FMOLS		DOLS (1,1)	DOLS (2,2)	FMOLS
pGDP	0.90*** (–20.11)	0.57 (–0.77)	0.96*** (–42.37)	BA	0.98*** (–75.43)	0.99*** (–10.35)	0.95*** (–45.29)
Obs	121	99	143	Obs	121	99	143
Central region							
Variable	Dependent variable: pGDP			Variable	Dependent variable: BA		
	DOLS (1,1)	DOLS (2,2)	FMOLS		DOLS (1,1)	DOLS (2,2)	FMOLS
BA	1.17*** (–26.27	1.91*** (–52.62)	1.21*** (–26.97)	pGDP	0.90*** (–8.34)	0.30 (–1.4)	0.83*** (–25.16)
Variable	Dependent variable: CO_2			Variable	Dependent variable: CO_2		
	DOLS (1,1)	DOLS (2,2)	FMOLS		DOLS (1,1)	DOLS (2,2)	FMOLS
pGDP	0.64*** (–10.6)	0.40*** (–4.28)	0.84*** (–28.26)	BA	0.99*** (–38.35)	1.03*** (–28.1)	0.98*** (–24.42)
Obs	88	72	104	Obs	88	72	104
Western region							
Variable	Dependent variable: pGDP			Variable	Dependent variable: BA		
	DOLS (1,1)	DOLS (2,2)	FMOLS		DOLS (1,1)	DOLS (2,2)	FMOLS
BA	1.24*** (–32.66)	1.35*** (–49.14)	1.29*** (–28.75)	pGDP	0.53*** (–5.90)	0.25 (–1.92)	0.79*** (–24.24)
Variable	Dependent variable: CO_2			Variable	Dependent variable: CO_2		
	DOLS (1,1)	DOLS (2,2)	FMOLS		DOLS (1,1)	DOLS (2,2)	FMOLS
pGDP	0.64*** (–7.24)	0.63*** (–1.36)	0.97*** (–29.77)	BA	1.27*** (–43.92)	1.29*** (–41.09)	1.24*** (–27.96)
Obs	88	72	104	Obs	88	72	104

Notes: BA and pGDP are built-up area and per capita GDP, respectively. The *t*-values are in parentheses. The panel method was grouped estimation. A panel data model with fixed effects was adopted. All tests were performed on the natural logarithm of the dependent and independent variables. Obs is observations. *, **and*** indicate the estimates are statistically significant at the 10%, 5% and 1% level, respectively.

assumption of one lead, one lag or tow leads, two lags in the change of the regressors (Li *et al*., 2011). The DOLS estimators were thus sensitive to the choice of number of lags and leads. But the most coefficients from DOLS estimation in our sample varied only slightly for different lags and leads. For the whole China, all estimated coefficients were positive and statistically significant at the 1% level when using pGDP, CO_2 and built-up area as dependent variables. The results suggest that urban expansion had a positive impact on economic growth and CO_2 emissions in China. In turn, economic growth contributed to the expansion of urban built-up area, and more people clustered in cities, which increases energy consumption and accordingly generates more emissions (Cole and Neumayer, 2004). More specifically, a 1% expansion in urban built-up area increases per capita income by approximately 0.81%–0.94%. A 1% increase in per capita income contributes to the expansion in urban built-up area by 0.66%–0.93% when using built-up area as the dependent variable. When using CO_2 emissions as the dependent variable, every 1% rise in land urbanization rate increases CO_2 emissions by approximately 1.15%–1.19%, and every 1% increase in per capita income increases CO_2 emissions by 0.60%–0.94%.

At the regional level, most estimated coefficients were also positive and statistically significant at the 1% level when using pGDP, CO_2 and built-up area as dependent variables. The urban expansion had a positive and significant impact on economic growth for the three regions, but the impact in the western region was slightly higher than that in the central and eastern regions. A 1% expansion in the build-up area contributes to the increase in per capita income by approximately 1.24%–1.35% in the western region, 1.17%–1.91% and 0.99%–1.03% in the central and eastern regions, respectively. In turn, economic growth also promoted to the expansion in urban built-up area. Specifically, every 1% rise in income per capita contributes to the expansion in built-up area by 0.66%–1.06% in the eastern region, 0.83%–0.90% and 0.53%–0.79% in the central and western regions, respectively. Meanwhile, both economic development and built-up area expansion also promoted to carbon emissions at the regional scale. A 1% increase in per capita income contributes to the increase in CO_2 emissions by approximately 0.90%–0.96% in eastern China, 0.40%–0.84% and 0.63%–0.97% in central and western China, respectively. Every 1% rise in urban expansion increases CO_2 emissions by about 0.95%–0.99% in the eastern region, 0.98%–1.03% and 1.24%–1.29% in the central and western regions, respectively. The impact of urban expansion to CO_2 emissions in the western region was larger than that in the eastern and central parts, whereas the effect of economic growth to emissions in the eastern region was larger than that in the western and central regions. This could be explained by the fact that in the eastern region, the increasing urban population, the scarcity of urban land, the competitive pressures of markets and advanced technology encourage the substitution of traditional energy sources by more flexible and reliable energy sources, which contribute to the reduction in proportion of coal use in energy consumption (Wang and Lin, 2012). On the other hand, the level of economic development in the eastern region was higher that than in the central and western regions. The economic development was positively associated with energy consumption (Bai *et al*., 2012). Therefore, the rapid economic growth and more energy consumption in the eastern region inevitably emit more CO_2 than that in the western and central regions.

The relationship between the growth rate in per capita income, built-up area and CO_2

emissions of China was displayed in Table 5. The correlation between per capita income and built-up area growth was statistically insignificant at the 5% level or higher. But the growth rate in economy and urban expansion had a significant and positive impact on CO_2 emissions in China, and economic growth had a larger effect on emissions than urban expansion. A 1% increase in economic growth contributes to the increase in CO_2 emissions by 1.76%–3.22%, and every 1% rise in urban expansion increases emissions by about 0.30%–0.80% in the eastern region.

Table 5 Panel cointegration coefficients by FMOLS and DOLS for China based on the growth rate of all variables

Variable	Dependent variable: pGDP growth			Variable	Dependent variable: BA growth		
	DOLS (1,1)	DOLS (2,2)	FMOLS		DOLS (1,1)	DOLS (2,2)	FMOLS
BA growth	0.07 (1.29)	0.04 (0.46)	0.06 (3.16)	pGDP growth	–0.06 (–0.09)	2.52 (1.13)	0.62 (2.30)
Variable	Dependent variable: CO_2 growth			Variable	Dependent variable: CO_2 growth		
	DOLS (1,1)	DOLS (2,2)	FMOLS		DOLS (1,1)	DOLS (2,2)	FMOLS
pGDP growth	2.58*** (5.47)	3.22** (2.00)	1.76*** (7.01)	BA growth	0.53*** (3.99)	0.80*** (2.25)	0.30*** (4.97)
Obs	310	248	372	Obs	310	248	372

Notes: BA and pGDP are the growth rate of built-up area and per capita GDP, respectively. The *t*-values are in parentheses. The panel method was grouped estimation. A panel data model with fixed effects was adopted. All tests were performed on the natural logarithm of the dependent and independent variables. Obs is observations. **and*** indicate the estimates are statistically significant at the 5% and 1% level, respectively.

4.4 Granger causality tests

4.4.1 Granger causality tests based on panel VECM

Table 6 lists the Granger causality test results based on panel VECM for the whole China and its three regions. Bidirectional long-run causalities between land urbanization (built-up area expansion), economic growth, and CO_2 emissions existed at the national level. Whereas there are only unidirectional short-run causal linkages running from: economic growth to land urbanization; land urbanization to CO_2 emissions; and economic growth to CO_2 emissions (Figure 3). Specifically, economic growth contributed to urban expansion, but not vice versa (Panel A), which is not in agreement with a previous study showing long- and short-run unidirectional causality between economic growth and land urbanization in China (Bai *et al*., 2012). Further, it can be found that both land urbanization and economic growth were the Granger cause of CO_2 emissions, but not vice versa (Panel B and C).

At the regional scale, a bidirectional long-run causality between land urbanization and economic growth was found in the eastern and central regions (Panel D and G). But there exist only unidirectional long- and short-term causal linkages running from: land urbanization to CO_2 emissions (Panel E and F); and economic growth to CO_2 emissions in the eastern and central regions (Panel H and I). Both no long- and short-term causal relationship between land urbanization, economic growth and CO_2 emissions was detected in the western region (Table 6).

Table 6 Wald F-test statistics based on panel-based vector error corrected models for the whole China and its eastern, central and western regions

	Panel	Causal	Result	F-statistic value	
				Short-run causality	Long-run causality
Whole China	A	pGDP	BA	15.237 (0.00)	192.31 (0.00)
		BA	pGDP	7.204 (0.12)	6421.924 (0.00)
	B	BA	CO_2	18.446 (0.00)	313.338 (0.00)
		CO_2	BA	17.518 (0.10)	194.408 (0.00)
	C	pGDP	CO_2	9.019 (0.05)	6331.291 (0.00)
		CO_2	pGDP	4.444 (0.34)	305.076 (0.00)
Eastern region	D	pGDP	BA	0.635 (0.73)	14.571 (0.01)
		BA	pGDP	3.562 (0.17)	28.332 (0.00)
	E	BA	CO_2	5.004 (0.05)	8.156 (0.00)
		CO_2	BA	6.806 (0.16)	19.042 (0.15)
	F	pGDP	CO_2	3.373 (0.04)	10.885 (0.02)
		CO_2	pGDP	2.385 (0.30)	59.190 (0.10)
Central region	G	pGDP	BA	0.708 (0.70)	12.490 (0.01)
		BA	pGDP	3.116 (0.21)	110.951 (0.00)
	H	BA	CO_2	10.981 (0.00)	19.285 (0.00)
		CO_2	BA	3.562 (0.16)	10.308 (0.12)
	I	pGDP	CO_2	2.640 (0.05)	13.521 (0.00)
		CO_2	pGDP	12.367 (0.14)	133.69 (0.10)
Western region	J	pGDP	BA	0.231 (0.89)	2.928 (0.71)
		BA	pGDP	3.988 (0.13)	53.577 (0.10)
	K	BA	CO_2	2.112 (0.35)	6.898 (0.22)
		CO_2	BA	3.018 (0.22)	6.749 (0.15)
	L	pGDP	CO_2	1.749 (0.42)	4.501 (0.34)
		CO_2	pGDP	1.086 (0.58)	169.38 (0.34)

Notes: The null hypothesis is non-causality. BA, pGDP and CO_2 are built-up area, per capita GDP and CO_2 emissions, respectively. Cases with probability levels (shown in parentheses) lower than 0.05 reject the null hypothesis.

4.4.2 Heterogeneous panel Granger causality tests

Table 7 provides the heterogeneous panel Granger causality test results for the whole China and its eastern and western regions[2]. These findings further verified the presence of unidirectional short-term causal linkages between urbanization, economic growth and CO_2 emissions at the national level. The short-run causalities from economic growth to land urbanization were detected in both Lag 1 and Lag 2 models. Land urbanization was the short-run Granger cause of CO_2 emissions in both Lag 1 and Lag 2 models, but not vice versa. In addition, the short-run Granger causality from economic growth to CO_2 emissions was also found both in Lag 1 and Lag 2 models, but the causal relation from CO_2 emissions to

[2] Heterogeneous panel Granger causality test results for the central region was not given due to the number of cross-section in this region less than 9. Dumitrescu and Hurlin (2012) causality tests require the cross-sectional number greater than or equal to 9.

Table 7 Heterogeneous panel Granger causality test results for the China and its eastern and western regions

	Panel	Causal	Result	Wald-static	Zbar-static	Probability
Whole China	A	pGDP	BA	Lag 1: 2.052	Lag 1: 2.063	0.04
				Lag 2: 5.458	Lag 2: 3.460	0.00
		BA	pGDP	Lag 1: 3.743	Lag 1: 6.411	0.10
				Lag 2: 3.207	Lag 2: 0.530	0.60
	B	BA	CO_2	Lag 1: 10.190	Lag 1: 22.990	0.00
				Lag 2: 10.792	Lag 2: 10.403	0.00
		CO_2	BA	Lag 1: 1.537	Lag 1: 0.739	0.46
				Lag 2: 3.742	Lag 2: 1.226	0.22
	C	pGDP	CO_2	Lag 1: 7.138	Lag 1: 15.143	0.00
				Lag 2: 12.426	Lag 2: 12.531	0.00
		CO_2	pGDP	Lag 1: 1.789	Lag 1: 1.386	0.17
				Lag 2: 4.363	Lag 2: 2.035	0.04
	Panel	Causal	Result	W-static	Zbar-stat	Porb.
Eastern region	D	pGDP	BA	Lag 1: 1.729	Lag 1: 0.735	0.46
				Lag 2:3.052	Lag 2: 0.196	0.84
		BA	pGDP	Lag 1: 3.643	Lag 1: 3.665	0.00
				Lag 2: 7.598	Lag 2: 3.721	0.00
	E	BA	CO_2	Lag 1: 9.610	Lag 1: 12.806	0.00
				Lag 2: 7.604	Lag 2: 3.725	0.00
		CO_2	BA	Lag 1: 1.514	Lag 1: 0.404	0.69
				Lag 2: 3.502	Lag 2: 0.554	0.59
	F	CO_2	pGDP	Lag 1: 0.953	Lag 1: –0.454	0.65
				Lag 2: 3.680	Lag 2: 0.683	0.49
		pGDP	CO_2	Lag 1: 6.039	Lag 1: 7.336	0.00
				Lag 2: 15.939	Lag 2: 10.189	0.00
	Panel	Causal	Result	W-static	Zbar-stat	Porb.
Western region	J	pGDP	BA	Lag 1: 2.006	Lag 1: 0.987	0.32
				Lag 2: 5.319	Lag 2: 1.666	0.10
		BA	pGDP	Lag 1: 4.519	Lag 1: 4.271	0.10
				Lag 2: 5.262	Lag 2: 1.628	0.10
	K	BA	CO_2	Lag 1: 7.959	Lag 1: 8.765	0.09
				Lag 2: 11.269	Lag 2: 5.601	0.25
		CO_2	BA	Lag 1: 1.566	Lag 1: 0.412	0.68
				Lag 2: 1.266	Lag 2: –0.014	0.31
	L	CO_2	pGDP	Lag 1: 1.643	Lag 1:0.513	0.61
				Lag 2: 4.694	Lag 2: 1.252	0.21
		pGDP	CO_2	Lag 1: 8.808	Lag 1: 9.873	0.35
				Lag 2: 13.559	Lag 2: 7.114	0.68

Notes: The null hypothesis is homogeneous non-causality. Cases with probability levels lower than 0.05 reject the null hypothesis. Lag 1 and Lag 2 represent the test models of the Dumitrescu and Hurlin (2012) causality tests of lag order 1 and 2, respectively.

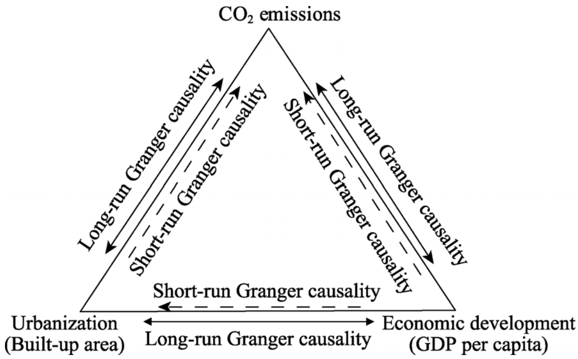

Figure 3 Long- and short-run Granger causality between land urbanization, economic growth and CO_2 emissions in China

economic growth was detected only in Lag 2 model (Table 7). These results indicated that both land urbanization and CO_2 emissions have little or no short-run impact on economic growth in China between 1997 and 2010. At the regional scale, we also further discovered the unidirectional short-term causal linkages running from land urbanization to CO_2 emissions and from economic growth to CO_2 emissions in the eastern region. Meanwhile, we also detected the presence of the unidirectional short-term causality between economic growth and land urbanization in the eastern region. The short-run Granger causality relationship between land urbanization, economic growth and CO_2 emissions in the western region were not found.

5 Validation of the EKC hypothesis in China

To further validate the EKC hypothesis in China, the Hausman test was performed to determine which one should be selected from two models: random effect and fixed effect models. Based on the assumption of the random effect model, the null hypothesis should be rejected for both quadratic and cubic models at the 1% significance level, which means that the fixed effect model may be more suitable than the random effect (Table 8).

Table 8 Hausman test results

Test summary	Chi-Sq. statistic	
Chi-Sq. statistic	Quadratic	Cubic
	40.304	41.210
Prob.	0.000	0.000
Accept model	Fixed effects	Fixed effects

Table 9 shows the estimates from the panel OLS estimator. For quadratic model, economic growth and urbanization had a positive and significant impact on CO_2 emissions. But the estimated coefficient on income squared was statistically insignificant at the 5% level. For cubic model, all the coefficients in the panel OLS equation were statistically significant at the 1% level or lower. Furthermore, the Wald test was also performed to choose the most appropriate one between the quadratic and cubic models. Results showed that the null hypothesis (the quadratic model) be rejected at the 1% significance level, indicating that the cubic function was more preferable to be accepted. From the sign of the parameters, there existed an inverse N-shape relationship between economic growth and CO_2 emissions in China. This demonstrates that as economic develops, CO_2 emissions fist decrease, and then rise after the left turning point and it will decline at last when arrive at the right turning point. By calculation, the left turning point was quite low and real GDP per capita was approximately 127 yuan (1997 prices) and the right turning point was approximately 10,201 yuan. These results further confirmed that land urbanization had a positive and significant impact on CO_2 emissions in China, implying that China's urbanization, especially land urbanization, does contribute to CO_2 emissions in the long-run.

Our empirical findings do not support the EKC hypothesis, which is in agreement with

Table 9 Estimation results in pGDP and CO_2 emissions based on the panel OLS estimator

Dependent variable [ln (CO_2)]	Quadratic model			Cubic model		
	Coefficient	t-statistic	Prob.	Coefficient	t-statistic	Prob.
ln(pGDP)	0.674	3.054	0.000	–6.336	–2.402	0.017
$\ln(pGDP)^2$	–0.003	–0.184	0.854	0.997	2.657	0.008
$\ln(pGDP)^3$	–			–0.047	–2.666	0.008
ln(BA)	0.293	8.239	0.000	0.286	8.089	0.000
Constant	–1.717	–2.247	0.025	14.589	2.368	0.018
Turning point	–			(127.41, 10201.29)		
F-statistic	597.542		0.000	589.035		0.000
Adjusted R^2	0.980			0.980		
Wald test	H_0: the quadratic model; H_1:the cubic curve					
Wald statistic	7.110^{***}					

Note: Fixed effect OLS estimator was used. The number of samples was 434. "***" indicates the estimator of a parameter is significant at the 1% level.

Table 10 Comparison with the other studies

Source	Data type	Method	Result
Jalil and Mahmud, 2009	China; Time series (1975–2005)	ARDL, quadratic model; VECM; EKC hypothesis	Inverted U-shaped, GDP→ CO_2
Wang *et al.*, 2011	China's 28 provinces; panel data (1995–2007)	Pedroni cointegration; Panel VECM; EKC hypothesis	U-shaped curve; GDP→CO_2 (long-run)
Du *et al.*, 2012	China's 28 provinces; panel data (1995–2009)	Quadratic and cubic models; EKC hypothesis; GMM estimator	Inverted U-shaped is not strongly supported
Wang *et al.*, 2012a	Beijing; Time series (1997–2010)	STIRPAT; OLS	Not support for EKC
This study	China's 31 provinces; panel data (1997–2010)	Pedroni cointegration; Panel VECM; EKC hypothesis; OLS; cubic model	Long-run: BA↔GDP; BA↔CO_2; GDP↔CO_2; short-run: GDP→BA; BA→ CO_2; GDP→CO_2; inverted N-shaped curve

Note: ARDL refers to the auto regressive distributed lag; GMM represents the generalized method of moment; OLS is the ordinary least square; and STIRPAT refers to the stochastic impacts by regression on population, affluence and technology. The symbol "↔", "→" represent the bidirectional and unidirectional Granger causality, respectively.

previous studies (Wang *et al.*, 2011; Wang *et al.*, 2012a; Du *et al.*, 2012). In addition to the differences as summarized in Table 10, a major difference is that the models we employed are different from those used by Jalil and Mahmud (2009), which may have an impact on the validity of EKC hypothesis. The quadratic model in the regression equations was used in the study by Jalil and Mahmud (2009). More importantly, the studies by Wang *et al*. (2012a), and Jalil and Mahmud (2009) were based on the time series data while our study performed a panel data analysis using the China's provincial data. It is generally acknowledged that panel data models have several major advantages over conventional cross-sectional or time series data models (Wang *et al*., 2014). Panel data models allow controlling for individual heterogeneity, as well as identifying effects that cannot be detected in simple time series or cross-section data (Du *et al*., 2012). Our results further suggest that the relationship between economic growth and CO_2 emissions in China do not support the EKC hypothesis.

6 Discussion and conclusions

Based on a balanced panel data of 31 provinces in China over the period 1997–2010, this study used the cointegration and Granger causality analysis to investigate the relationship between urbanization, economic growth, and CO_2 emissions at the national and regional scales. Results show that there is long-term equilibrium relationship between land urbanization, economic growth, and CO_2 emissions in China between 1997 and 2010, which is supported by Bai *et al*. (2012). In the long-term, a 1% growth in real GDP per capita accelerates urban expansion by approximately 0.66%–0.93% and accordingly increases CO_2 emissions by about 0.60%–0.94% in China. In turn, a 1% expansion in urban built-up area increases real GDP per capita by 0.81%–0.94% and contributes to CO_2 emissions by 1.15%–1.19% in China, which is consistent with a previous study by Zhang and Lin (2012). This result is also supported by Ponce de Leon Barido and Marshall (2014), whose result from a panel data of 80 countries for the period 1983–2005 suggested that a 1% increase in urbanization raises CO_2 emissions by 0.95%. At the regional level, land urbanization had positive and significant influence on economic growth, showing that a 1% expansion in the build-up area contributes to the increase in per capita income by approximately 1.24%–1.35% in western China, 1.17%–1.91% and 0.99%–1.03% in central and eastern China, respectively. Conversely, economic growth also contributed to the expansion in urban built-up area. Urbanization not only had a significant positive impact on economic growth but also contributed to CO_2 emissions in China. This could be explained by the fact that urbanization leads to the accelerated development of public and private transport, consuming more energy and emitting more CO_2 (Wang *et al*., 2012a; Zhang and Lin, 2012). With the development of urbanization, the shift of resident lifestyles may change consumer needs and behaviors, requiring more energy consumption and leading to more CO_2 emissions (Zhang and Lin, 2012; Feng *et al*., 2012). Furthermore, both economic growth and land urbanization also increased CO_2 emissions for the three regions. The effect of the former to CO_2 emissions in the western region was larger than that in the eastern and central parts, whereas the effect of economic growth to emissions was larger in the eastern region than that in other two regions. China's rapid economic growth is closely related to the increasing CO_2 emission (Feng *et al*., 2013). Further investigations demonstrate that the growth rate in economic development and urban expansion had a significant and positive impact on CO_2 emissions in China but the impact of the former on emissions was greater than that the latter. As the urbanization level has reached a high level of approximately 66% in 2012 in the eastern region, further urbanization may be more difficult, thus its driving force on emissions is expected to be relatively small. To reduce CO_2 emissions, we should give up the old pattern of high pollution and energy use in exchange for economic growth. Our findings also suggest that the eastern region should reduce the GDP growth rate and the western region should focus more on the speed of urbanization. It would be necessary to optimize industrial structure, improve energy efficiency, make an appropriate reduction in secondary industrial proportion, and boost the upgrade of high energy consumption industry for eastern China. In the western region, considering the strongest impact of urbanization on CO_2 emissions and its abundant renewable resources (i.e., wind, water and solar energy), it is urgent to develop the utilization of renewable energy as an alternative to the traditional fuels. China's central region is characterized by energy-guzzling heavy industry base, thus promoting industrial restructuring and utilizing clean coal technology would be pivotal for its success of energy-saving and emission-reducing.

The panel Granger causality analysis results suggest that there exist long-run bidirectional causal linkage between land urbanization, economic growth and CO_2 emissions in China. A bidirectional long-run causality between land urbanization and economic growth also existed in the eastern and central regions. This indicates that land urbanization does have causal effect on economic growth; and it is not only the consequences of economic growth among provinces in China, but also the drivers of such growth, implying that China's CO_2 emissions would not decrease in a long time period since reducing CO_2 emissions may hinder economic growth to some extent. It is not the most feasible measure to reduce CO_2 emissions at the expense of sacrificing economic development for China. Instead, more realistic and feasible means for China to reduce CO_2 emissions is to control the pace of urbanization process and improve energy structure (Lin and Liu, 2010). In addition, the panel Granger causality analysis revealed bidirectional long-run causalities running: from land urbanization to economic growth and CO_2 emissions; and from economic growth to emissions. The heterogeneous panel Granger causality testing further verified the existence of unidirectional short-term causalities running from economic growth to urbanization and from urbanization (or economic growth) to CO_2 emissions in China, which are in agreement with previous studies (Jalil and Mahmud, 2009; Wang *et al*., 2011). At the regional scale, there exist only unidirectional short-term causal nexus running from land urbanization to CO_2 emissions and from economic growth to emissions in the eastern and central regions. Further investigations show that there was an inverted N-shaped relationship between CO_2 emissions and economic growth in our sample, not supporting the EKC hypothesis. The two turning points of GDP per capita for CO_2 emissions were approximately equal to 127 yuan and 10,201 yuan, respectively. China's per capita income has reached more than 30,000 yuan in 2012 and it has surpassed the left inflection point. We should be wary of the appearance in the next turning point again in energy-saving and emission-reducing in the future.

Urbanization is a dynamic and multidimensional process that caused profound changes in land use, economic structure, ecological and environmental aspects (Bloom *et al*., 2008; Glaeser, 2011; Bai *et al*., 2012). To realize the urban dream, China needs to face three policy challenges, i.e., land, people and the environment (Bai *et al*., 2014). Urbanization will be an important engine of economic growth in China in the future. Blind and excessive land exploitation in the process of rapid urbanization has contributed to the dramatic decrease of the country's arable land, raising concerns about food security (Gao *et al*., 2006; Chen *et al*., 2007; Wang *et al*., 2012b). As urbanization accelerates, the average annual cropland area used for construction in China has increased drastically from 1.3 million ha in 1990–2000 to more than 2 million ha in 2000–2010, further highlighting the conflict between urbanization and cropland conservation (Liu Jiyuan *et al*., 2014).

Rapid urbanization has also important effects on labor force, climate, and public health (Zhou *et al*., 2004; Yang *et al*., 2011; Gong *et al*., 2012; Yang, 2013). A majority of farmers have become peasant workers with accompanying processes of industrialization and urbanization from the early 1980s onwards. According to the National Migrant Workers Monitoring Survey Report 2012 issued by the National Bureau of Statistics of China (NBSC), the total number of national migrant workers reached 262.21 million with a growth rate of 3.9% in 2012. Because of the household registration system, many peasant workers cannot gain access to urban medical insurance, education and other public services without adequate social security (Bai *et al*., 2014). The majority of the rural-to-urban migrants are men and some family members have been left behind in rural communities, which results in a large left-behind population consisting of women, children, and the elderly. It is reported that there were approximately 58 million children, 47 million women and 40 million elderly have been left behind in rural communities by their migrant family members (XNA, 2011). These three left-behind groups have caused societal unrest and psychological development problems for children left behind (Yang, 2013). Furthermore, rapid urbanization has contributed to the warming of mean surface temperature of 0.05℃ per decade in southeast China and 0.04℃ per decade in the eastern region (Zhou *et al*., 2004; Yang *et al*., 2011). Meanwhile, urbanization would continue to increase population exposure to major risk factors for disease, especially those that relate to the challenging environmental and social conditions that dominate China's large cities (Gong *et al*., 2012). Therefore, more attention should be paid to such negative consequences of rapid urbanization.

Our empirical findings demonstrate that China's rapid urbanization and economic growth has exerted a positive and significant effect on CO_2 emissions, meaning that it might be difficult for China to control urban expansion and reduce CO_2 emission without sacrificing economic growth in the long-run. Under its current economic growth model, it is essential for China's government to control the pace of urbanization process and implement effective policies of environmental protection consistently. China's economic growth will be slowed down under the background of the current 'new normal' economic development, we should seize the opportunity to adjust the industrial structure, improve energy efficiency, slowdown and then gradually decrease CO_2 emissions growth.

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