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Impacts of urban scale on low-carbon development: evidence from 265 cities in China

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Introduction: With rapid urbanization and increasing greenhouse effect, low-carbon development is the integral factor of achieving sustainable development.

Methods: A comprehensive analysis framework is built to quantify the impact of urban scale on low-carbon development and we conduct empirical research on 265 cities during 2009–2019.

Results and Discussion: We find that: first, urban scale can significantly promote low-carbon development and this finding still holds after the robustness test. Specifically, for every 1% increase in urban scale, the low-carbon development level of the urban increases by 0.128%; second, urban scale promotes low-carbon development mainly through three paths: efficiency improvement, industrial structure upgrading, and innovation; third, there is heterogeneity in this effect among cities with different city levels, city structures, and traffic conditions. Therefore, we propose specific, targeted policy implications, including reducing restrictions on the expansion of large cities and promoting high-tech development.

KEYWORDS

urban scale, low carbon development, China, efficiency improvement, industrial structure upgrading, innovation

1 Introduction

Carbon emissions are considered to be the largest contributor to greenhouse effect, bringing many adverse consequences to human society, such as reduced food production and increased climate extremes (Ahmad et al., 2018; Xia et al., 2018). According to a study, global carbon emissions increased 3,285 times from 1751 to 2014. China has ranked first in the world in carbon emissions since 2007 and has a huge task to reduce emissions (Nejat et al., 2015; Nan et al., 2018; Jiang, 2022). Since 2008, 80% of the incremental carbon dioxide emissions have been emitted by China (Peters GP, et al., 2012). Regarding global warming, scientists and politicians have reached a consensus that the rising concentration of greenhouse gases, especially CO2, is the main cause of global warming (China, 2015; Huo et al., 2021).

Urban areas cover only 2% of the world's land area, but contribute over 70% of global carbon emissions (Xu et al., 2018; Liu et al., 2019; Yu et al., 2020). Since 1978, China's urbanization has achieved remarkable achievements, which has grown from 17.9% in 1978 to 65.2% in 2022, a change that is expected to reach 75% by 2050. As a concentration of production and consumption, cities consume most of the energy and emit huge amounts of carbon dioxide. Therefore, the main path to reduce CO2 in the future is to reduce

CO_2 emissions from cities and towns. China's total urban CO_2 consumption is three times higher than that of rural areas, and the *per capita* energy consumption is 6.8 times higher (Dhakal, 2009). Therefore, compared to rural areas, cities play a more decisive role in low-carbon development (Kennedy et al., 2010; Ahmad et al., 2018). How to balance the relationship between urbanization and carbon emission reduction will inevitably become an important issue for China to achieve sustainable development (Zhou et al., 2013a). Thus, studying the relationship between urbanization and low-carbon development can provide a reasonable basis for policy formulation.

There are usually two perspectives on research related to the topic of this paper: aggregate and efficiency perspectives. First, from an aggregate emissions perspective, most scholars believe that expanding urban scale will be detrimental to low-carbon development, that is, leading to an increase in carbon emissions. (Murtaugh and Schlax, 2009). Xia et al. (2019) empirically investigated the relationship between urban population size and total urban carbon emissions. The results showed that the increase in urban population promoted total carbon emissions. Fragkias et al. (2013), based on 1999–2008 from metropolitan areas, argue that CO_2 emissions are proportional to the size of urban population. A study by Bereitschaft and Debbage, (2013) found that high sprawl metropolitan areas show a concentration of high pollution and emissions. Jia et al. (2012) used 47 representative countries and regions worldwide as research samples. They found that urbanization development is one of the important means to promote low-carbon development.

Second, with the expansion of urban scale, it may contribute to a reduction in *per capita* carbon emissions (Liu et al., 2021). The reason may be that increasing the size of the urban population can increase the efficiency of the use of public facilities, and ultimately reduce CO_2 emissions. (Glaeser and Kahn, 2010; Zhou et al., 2019). used major metropolitan areas in the United States as a sample for their study and found that more populous cities were more energy efficient and emitted less carbon dioxide compared to less populous cities. Urban scale can reduce carbon emissions (Gottdiener et al., 2005; Martine, 2009; Satterthwaite, 2009). In the process of promoting emission reduction through urban scale, technological progress, efficiency improvement, and energy structure adjustment have played a crucial role. (Brown and Southworth, 2008; Mizobuchi, 2008; Ang, 2009). Using a sample of Guangdong Province in China, Yang et al. (2020) found that reduction of urban carbon emissions are largely dependent on improvements in energy efficiency.

It can be seen that, as an important urban characteristic, urban scale can directly affect CO_2 emissions (Smil, 2008; Payne, 2010). The existing literature provides a wealth of insights into the different perspectives on carbon reduction (Zhao et al., 2018), there are still areas where improvements can be made: first, most studies have used cross-provincial scales (Li, 2021; Wei et al., 2021). Therefore, it is difficult to highlight the unique characteristics of different cities. Second, there is little research on the mechanism of the impact of urban scale carbon on low-carbon development (Wang and Huang, 2019). Third, the current urban scale studies mostly analyze large cities or urban agglomerations, with insufficient coverage of national cities and only a few papers covering small city samples, while the use of large samples to explore the general pattern of carbon emission effects of urban form and the heterogeneity in different types of cities is extremely important for the realization of the vision of carbon neutrality in Chinese cities (Sun et al., 2014; Xu and Xu, 2021).

This paper expands on the following aspects: first, the use of prefectural city-level data can better reflect the dominance of cities in national carbon emissions, bridging the gap between existing studies in revealing regional and spatial differences in carbon emissions Second, a theoretical analysis framework of urban scale affecting low-carbon development is established, and the mechanism of urban scale influencing low-carbon development is systematically explored. Third, a rich heterogeneity test is added to the analysis of this paper to explore the impact of urban scale on low-carbon development in cities with different characteristics from different dimensions, which provides appropriate support for policy formulation.

The remainder of the article is organized as follows: Section 2 describes the mechanism analysis. Section 3 provides the research design and data. The empirical analysis is presented in Section 4. Section 5 provides the discussion. The conclusions and policy recommendations are discussed in Section 6.

2 Mechanism analysis

2.1 Direct effect

The expansion of urban scale can directly promote low-carbon development, which is mainly reflected in the following two aspects. First, the expansion of urban scale can lead to a flow of innovative factors from rural to urban areas, and the spillover and sharing of knowledge and technology within the city will be more convenient and efficient (Düben and Krause, 2020). In this process, the level of urban human capital, is enhanced, providing sufficient intellectual support for the research and ultimately promoting the low-carbon development of cities (Fan et al., 2007). At the same time, in larger cities, due to the market mechanism, the output of enterprises and workers is higher, which is beneficial to the scale and centralized production of products, improving the efficiency of urban production factors utilization, and promoting the efficiency of green economy, thus ultimately promoting low-carbon development (Payne, 2010; Wei and Yf, 2020). In conclusion, we put forward the following hypothesis1.

Hypothesis 1. Urban scale promotes low-carbon development.

2.2 Indirect effects

2.2.1 Efficiency improvement

Urban scale promotes low-carbon development through efficiency improvement. Specifically, the larger the city as an area of high concentration of economic activity, the greater the spatial externality it acquires, the larger the city, the greater its creativity and thus its ability to cope with the changing socioeconomic environment, and the more productive the city (Leo, 1975). As the urban scale expands, sharing the fixed costs of infrastructure and public services, promoting the matching of labor and enterprises, and knowledge spillover are the micro mechanisms of agglomeration economy formation (Rosenthal and Strange, 2006). Desmet and Rossi-Hansbergh, (2013) decomposes the determinants of urban scale distribution into urban efficiency, amenities and frictions, stating that higher productivity, better urban amenities will form larger cities. Kolpakov (2020) showed that efficiency improvements are decisive for the reduction of CO2 emissions. As the urban scale expands, the efficiency improvement significantly promotes low-carbon development (Melo et al., 2009; Li et al., 2015). In conclusion, we derive the following hypotheses:

Hypothesis 2. Urban scale promotes low-carbon development through efficiency improvement.

2.2.2 Industrial structure upgrading

Urban scale promotes low-carbon development through industrial structure upgrading. Specifically, in the process of continuously expanding the scale of Chinese cities, the industrial structure has also undergone tremendous upgrades and transformations; specifically, from 1978 to 2022, the tertiary industry increased from 24.6% to 52.8%. In other words, rapid urbanization is usually accompanied by industrial structure upgrading, because cities are the main host of service industries, and the proportion of tertiary industries will develop rapidly with rapid urbanization, which will in turn promote industrial structure upgrading. Studies have found that promoting industrial transformation and upgrading and changing economic development patterns are effective means to promote carbon emission reduction (Chuai and Feng, 2019; Li, 2021). Empirical studies show that industrial structure upgrading not only promotes the reduction of total carbon emissions, but also contributes to the reduction of carbon emission intensity (Cheng, 2018; Zhao et al., 2014). The impact of industrial structure upgrading on low-carbon development is not only seen in economically developed regions of China, but also in the central and western regions (Zhang et al., 2014). Therefore, we propose hypothesis 3.

Hypothesis 3. Urban scale promotes low-carbon development through industrial structure upgrading.

2.2.3 Technological innovation

Urban scale promotes low-carbon development through technological innovation. Specifically, urban expansion accelerates the accumulation of local human capital, which contributes to an increase in innovation activities and patent applications (Duncan and Vernon, 1999; Bettencourt and Lobo, 2007). Increased innovation capacity plays an important role in low-carbon development (Dong et al., 2018; Fare et al., 1994) Based on Data from Chinese Provinces. Yang et al. (2014) showed that high quality innovation can suppress carbon emission intensity and that inter-regional R&D spillover effects can significantly reduce carbon emission intensity. Cheng et al. (2017a) concluded that technological progress and innovation play a greater role in low carbon development compared to industrial structure. Therefore, we hypothesize the following hypotheses:

Hypothesis 4. Urban scale promotes low-carbon development through technological innovation.

3 Methodology and data

3.1 Econometric methodology

3.1.1 Basic model

As shown in Eq. 1, an empirical model was constructed to verify the impact of urban scale on low-carbon development.

$$lnld_{it} = \alpha_0 + \beta_1 lnpop_{it} + \beta_2 control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

Where, $lnld$ denotes low-carbon development; $lnpop$ denotes urban scale; μ_i and λ_t respectively characterize individual effect and time effect; $control_{it}$ denotes the control variables involved in this article; respectively, this paper focuses on the coefficient β_1, which indicates the effect of urban scale on low-carbon development after excluding the interference of other factors.

3.1.2 Intermediary effect model

As in the theoretical mechanism analysis above, urban scale may influence low carbon development through industrial structure upgrading, efficiency improvement and innovation. To further identify the existence of the three mechanisms of action, drawing on the test for mediating effects (Baron and Kenny, 1986), a three-step approach is used to test the model set as follows:

$$lnld_{it} = \alpha_0 + \beta_1 lnpop_{it} + \beta_2 control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

$$W_{it} = \alpha_0 + \alpha_1 lnpop_{it} + \varphi control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

$$lnld_{it} = \alpha_0 + \alpha_3 WM_{it} + \theta W_{it} + \Phi control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (4)$$

Where, W is the mediating variable. According to the test of mediating effect, the baseline regression of Eq. 2 is used to verify the effect of urban scale on low carbon development; the second step regresses Eq. 3, focusing on the coefficient estimate α_1, to examine the relationship between urban scale and mediating variables; the third step estimates Eq. 4, and if the values of λ, α_3 and θ are significant then the mediating effect exists.

3.2 Variable selection

Explained variable: low carbon development (*lnld*). Most previous studies have used total carbon emissions to measure low-carbon development (Chuan, 2019; Sueyoshi et al., 2019). However, for China, due to its large population base, changes in total carbon emissions cannot reasonably reflect carbon emission efficiency. In contrast, carbon emission intensity better reflects China's low-carbon development. Therefore, referring to the study by Tian et al. (2019) and Zhang, (2014), we constructed Eq. 5:

$$CE_{energy} = \sum_{i=1}^{8} CE_i = \sum_{i=1}^{8} E_i \times NCV_i \times ECF_i \times COF_i \times \frac{44}{12} \quad (5)$$

Where, CE_{energy} represents the carbon emission, E_i is the amount of energy consumed, NCV_i is the low calorific value, ECF_i represents the carbon content supplied by Change, (2007), and COF_i represents the carbon oxidation rate. Ld is set to Eq. 6:

$$Ld_{it} = \left(CE_{energy}\right)_{it} / GDP_{it} \quad (6)$$

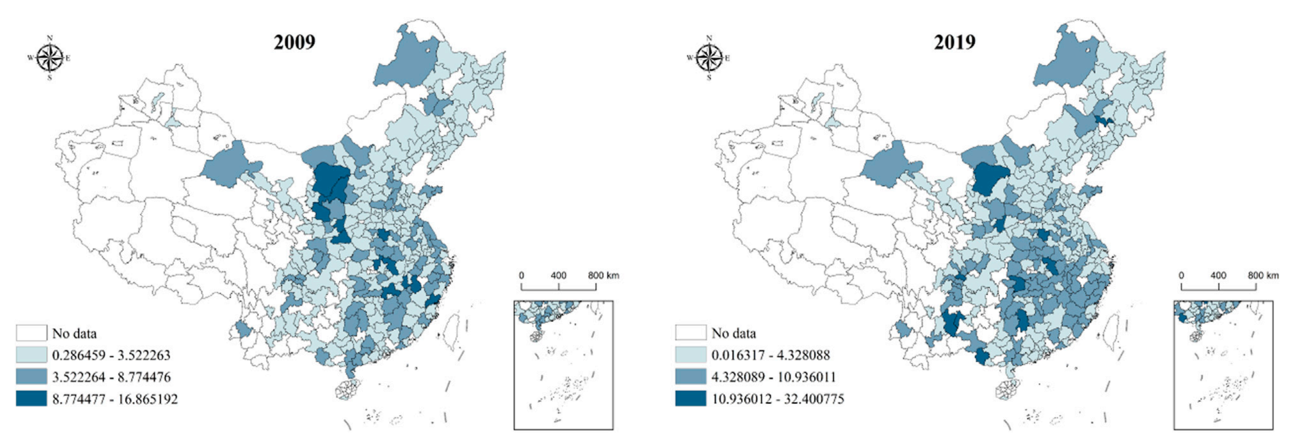

FIGURE 1
The low-carbon development in 2009 and 2019.

Where, Ld_{it} is the low carbon development level, $(CE_{energy})_{it}$ is the carbon emission of city i in year t, and GDP_{it} is the regional GDP of city i in year t. We show the low carbon development level of 265 cities in China in 2009 and 2019 in the form of maps to analyze their spatial distribution characteristics more intuitively. (see Figure 1). From a dynamic perspective, compared with 2009, the vast majority of Chinese cities in 2019 have increased their low-carbon development levels; from a static perspective, first, there are large differences in low-carbon development levels between different cities in China, with the eastern region experiencing rapid development while the central and western regions lagging behind; Second, large cities have significantly higher levels of low-carbon development compared to small and medium-sized cities, mainly because of their good urban infrastructure, innovation capacity and industrial structure.

Core explanatory variable: urban scale ($lnpop$). As an important urban characteristic, population size may affect energy consumption in urban areas, which in turn directly affects CO2 emissions. For this reason, this paper uses city year-end population to characterize urban scale. (Smil, 2008; Glaeser and Kahn, 2010; Payne, 2010; Fragkias et al., 2013).

Intermediate variables: based on the previous theoretical analysis, we selected efficiency (*tfp*), industrial structure (*ind*) and innovation (*inno*) as mediating variables in this paper, respectively. Specifically:

(1) industrial structure upgrading (*ind*). We refer to Cheng et al. (2017b) and use the share of tertiary sector output to GDP to portray the industrial structure upgrade upgrading.
(2) Efficiency (*tfp*). Total factor productivity is used to portray efficiency. Specifically, referring to the study by Kuang (2020), we used the DEA-Malmquist method to measure efficiency.
(3) Innovation (*inno*). For the measure of innovation level, the amount of patents granted is used to better measure the quality rather than the quantity of innovation.

Control variables: *GDP*,urbanization (*urb*), financial development (*fin*) and government intervention (*gov*). We use ratio of urban population to total population to characterize *urb*, year-end stock of financial institutions to measure *fin*, and financial expenditure as a percentage of total expenditure to measure *gov*.

TABLE 1 Statistical description of variables.

Variable	Obs	Mean	Std. Dev	Min	Max
lnld	2,904	1.013	0.098	0.600	1.564
lnpop	2,904	2.572	0.292	1.290	3.534
lnpgdp	2,904	10.508	0.721	8.650	12.879
Fin	2,904	1.393	0.703	0.371	20.100
Gov	2,904	0.185	0.086	0.044	1.485
Urb	2,904	0.404	0.235	0.075	1.819
Ind	2,904	0.402	0.100	0.098	0.835
Inno	2,904	2.432	1.190	0.021	6.280
Lntfp	2,904	0.921	0.308	0.099	1.373

3.3 Data source

This study focuses on 265 prefecture-level cities in China for the period 2009–2019. The data required to calculate urban carbon emissions urban population data as well as other data were mainly obtained from statistics such as China Urban Statistical Yearbook, China Statistical Yearbook. Statistical descriptions for all variables are presented in Table 1.

4 Empirical results

4.1 Basic regression results

Table 2 shows the correlation coefficients between all variables and core explanatory. Table 3 lists the regression results of urban scale on low-carbon development estimated by FE models and RE models. After the Hausman test, the FE model times was chosen to explain the regression results. The results show that the regression

TABLE 2 The correlation coefficients between all variables and core explanatory.

Variable	*lnld*	*lnpop*	*lnpgdp*	*fin*	*gov*	*urb*	*ind*	*inno*	*lntfp*
lnld	1.0000								
lnpop	0.122***	1.0000							
lnpgdp	0.268***	−0.068***	1.0000						
fin	0.165***	0.025	0.230***	1.0000					
gov	−0.116***	−0.179***	−0.443***	0.197***	1.0000				
urb	0.159***	−0.157***	0.620***	0.326***	−0.202***	1.0000			
ind	0.229***	0.107***	0.428***	0.599***	0.062***	0.368***	1.0000		
inno	0.223***	0.100***	0.655***	0.265***	−0.388***	0.373***	0.399***	1.000	
lntfp	0.031*	−0.002	−0.047**	0.000	−0.025	−0.011	0.005	−0.013	1.0000

TABLE 3 Basic regression results.

Variable	FE	FE	RE	RE
	(1)	(2)	(3)	(4)
lnpop	0.186***	0.128**	0.053***	0.049***
	(0.053)	(0.054)	(0.016)	(0.015)
lnpgdp		0.031***		0.033***
		(0.006)		(0.005)
fin		0.015***		0.015***
		(0.003)		(0.003)
gov		−0.032		−0.028
		(0.031)		(0.026)
urb		0.002		−0.004
		(0.024)		(0.017)
Hausman	6.95 (0.0084)	6.20 (0.0449)		
_cons	0.534*** (0.136)	0.345** (0.139)	0.878*** (0.040)	0.528*** (0.057)
N	2915	2904	2915	2904
Time effect	Yes	Yes	Yes	Yes
Individual effect	Yes	Yes	Yes	Yes
R-sq	0.0148	0.0752	0.0148	0.1014

***,**, and* indicate significance at 1%, 5%, and10% levels, respectively, Figures in () are the p -values.

coefficient of urban scale on low-carbon development is 0.186, indicating that urban scale significantly contributes to low-carbon development. After adding further control variables, the coefficient of urban scale on low carbon development is 0.128 and significant at the 5% level of significance.

4.2 Intermediary effects

The results of model (1) in Table 4 show that the estimated coefficient of the effect of urban scale on innovation improvement is 0.001, and that urban scale has a facilitating effect on innovation improvement. From model (2), it can be seen that urban scale can indirectly contribute to low carbon development through the positive impact of innovation. Specifically, each unit increase in urban scale directly increases low carbon development by 0.120 units and also contributes to 0.001 units increase in innovation capacity. Models (3) and (4) are the estimated results with industrial structure upgrading as the mediating variable. The estimated coefficient of urban scale on industrial structure upgrading is 0.002 and the coefficient of industrial structure upgrading on low carbon development is 0.001, indicating that

TABLE 4 Regression results for the intermediate effects.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	Technological innovation		Industry structure		Efficiency improvement	
	Inno	Ce	Ind	Ce	Tfp	Ce
lnpop	0.001*** (0.000)	0.120** (0.053)	0.002*** (0.000)	0.091* (0.054)	0.005*** (0.002)	0.131** (0.054)
W		0.001*** (0.000)		0.001*** (0.000)		0.005*** (0.002)
lnpgdp	0.032***	0.029***	0.013*	0.012*	0.036***	0.033***
	(0.006)	(0.006)	(0.007)	(0.007)	(0.006)	(0.006)
fin	0.015***	0.015***	0.012***	0.012***	0.015***	0.015***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
gov	−0.032	−0.031	−0.056*	−0.054*	−0.033	−0.032
	(0.031)	(0.031)	(0.031)	(0.031)	(0.031)	(0.031)
urb	−0.025	−0.015	−0.018	−0.010	−0.010	−0.000
	(0.024)	(0.024)	(0.024)	(0.024)	(0.024)	(0.024)
_cons	0.653***	0.368***	0.819***	0.591***	0.625***	0.313**
	(0.053)	(0.138)	(0.065)	(0.150)	(0.054)	(0.139)
Time effect	Yes	Yes	Yes	Yes	Yes	Yes
Individual effect	Yes	Yes	Yes	Yes	Yes	Yes
N	2904	2904	2904	2904	2904	2904
R2	0.0486	0.0614	0.0837	0.0749	0.0871	0.0775

***,**, and* indicate significance at 1%, 5%, and10% levels, respectively, Figures in () are the *p* -values.

urban scale enhances low carbon development through the positive mediating effect of industrial upgrading. Similarly, with models (5) and (6), we find that urban scale promotes low-carbon development by increasing efficiency and hence, low-carbon development. The mechanism hypothesis in the previous section is verified.

4.3 Heterogeneity

The heterogeneity in Table 5 is shown mainly in terms of city level, city structures and transportation:

First, in this paper, cities are divided into central cities and peripheral cities. In particular, this effect is not significant in peripheral cities. Second, the urban spatial structure is divided into polycentric structure and monocentric structure, and the results are listed in Table 5. We can find that the coefficient of the effect of urban scale on low-carbon development in polycentric cities is 1.153 and passes the 1% significance test, while this effect is not significant in monocentric cities. At last, considering the convenience of transportation, this paper divides cities into two groups according to whether or not high-speed rail is opened. We can find that the coefficient of the effect of urban scale on low-carbon development in cities with high-speed rail is 0.304, while this effect is not significant in cities without high-speed rail.

Table 6 shows the robustness tests we performed to enhance the credibility of the study. First, we replace the core explanatory variables. Unlike the previous paper that focuses on efficiency measures, we re-measure the low-carbon development indicators in terms of aggregates and run a re-regression, and find that urban scale significantly suppresses carbon emissions, suggesting that low-carbon development helps promote low-carbon development. Second, this study was re-estimated using data from 2014 to 2019. Third, we exclude the municipalities and run the regression again. All three robustness tests demonstrate that urban scale significantly contributes to regional low-carbon development, which indicates that our findings are robust.

5 Discussion

5.1 Analysis of the direct effect

With the development of urbanization, a number of internationally renowned large cities are emerging in China (Jia et al., 2023). First, only when the size of the city expands to a certain extent, the increase in *per capita* income makes it put more energy and money into environmental protection, which ultimately contributes to the enhancement of the efficiency of carbon emission; second, the expansion of the size of the city is conducive to the transformation of the mode of economic development, accelerating the development of production and consumption in the direction of greening and coordinating, which in turn enhances the efficiency of carbon emission.

TABLE 5 Heterogeneity test.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
lnpop	0.329***	0.008	1.153***	−0.035	0.304***	−0.092
	(0.113)	(0.059)	(0.326)	(0.062)	(0.069)	(0.101)
lnpgdp	0.222***	0.013**	0.055**	0.011*	0.094***	0.010
	(0.019)	(0.006)	(0.026)	(0.006)	(0.009)	(0.010)
fin	0.005	0.017***	0.000	0.017***	0.009***	0.015
	(0.011)	(0.003)	(0.032)	(0.003)	(0.003)	(0.011)
gov	−0.177	−0.018	−0.612	−0.015	0.153*	−0.033
	(0.225)	(0.031)	(0.386)	(0.031)	(0.081)	(0.038)
urb	−0.166***	−0.022	−0.093	−0.029	−0.049	−0.032
	(0.064)	(0.025)	(0.064)	(0.028)	(0.030)	(0.054)
_cons	−2.179***	0.838***	−2.560***	0.968***	−0.804***	1.129***
	(0.330)	(0.151)	(0.821)	(0.158)	(0.188)	(0.260)
N	374	2530	176	2354	1450	1454
Time effect	Yes	Yes	Yes	Yes	Yes	Yes
Individual effect	Yes	Yes	Yes	Yes	Yes	Yes
R2	0.4437	0.0327	0.0515	0.0018	0.046	0.158

***,**, and* indicate significance at 1%, 5%, and10% levels, respectively, Figures in () are the p -values.

TABLE 6 Robustness tests.

Variable	Replace digital economy indicator	Change research period	Exclude municipalities
lnpop	−3.496***	0.190***	0.095*
	(1.248)	(0.072)	(0.052)
lnpgdp	1.106***	0.077***	0.024***
	(0.133)	(0.012)	(0.006)
fin	−0.117	0.007***	0.015***
	(0.071)	(0.003)	(0.003)
gov	−0.685	0.214***	−0.031
	(0.723)	(0.048)	(0.030)
urb	2.379***	−0.041	0.015
	(0.559)	(0.040)	(0.023)
_cons	−0.822	−0.332	0.496***
	(3.223)	(0.219)	(0.134)
N	2904	1584	2860
Time effect	Yes	Yes	Yes
Individual effect	Yes	Yes	Yes
R-sq	0.2946	0.1160	0.0882

***,**, and* indicate significance at 1%, 5%, and10% levels, respectively, Figures in () are the p -values.

5.2 Analysis of the intermediary effect

The mechanism through which urban scale affects low carbon development is mainly manifested in the following aspects:

First, innovation plays an irreplaceable role in the impact of urban scale on low-carbon development. On the one hand, the expansion of urban scale can accommodate people with different industrial and professional backgrounds, gathering more talents, capital and policy dividends, and possessing a more inclusive and open innovation support environment; on the other hand, the expansion of urban scale leads to the spatial aggregation of perfect industrial chains, promoting the diffusion of knowledge and technology, and forming an effective knowledge Complementary. In other words, innovation is the result of the expansion of urban scale, and it is also the main factor of low-carbon development.

Second, urban scale promotes low-carbon development through efficiency improvement. The rapid development of urbanization has promoted the reconfiguration of factors such as labour among different cities. As cities expand, their ability to cope with changing socio-economic environments increases, as does their productivity. Rapid urban expansion generates high agglomeration economic benefits, which drives significant increases in urban efficiency and, ultimately, in carbon emission efficiency.

Third, the expansion of urban scale has increased the demand for labor, thus providing the possibility for urban-rural mobility of labor elements and population concentration, which is mainly manifested in the transfer of agricultural employees to the secondary and tertiary industries for employment, while high-quality labor continues to flow into the city, providing the basis for industrial upgrading. Obviously, the result of industrial upgrading is that the proportion of the tertiary industry, which has a smaller total carbon emission, is increasing, which promotes the low-carbon development of the city.

5.3 Analysis of the heterogeneity

Urban heterogeneity and diversity are important sources of promoting economic growth and carbon emissions, which are reflected in city level, city structure, and transportation conditions:

China's urban levels have distinct heterogeneity characteristics, with different levels of cities having varying levels of authority, resource allocation capabilities, and political capital. In China's economic development, administrative resource allocation is crucial (Luo et al., 2017). Specifically, firstly, cities with high administrative level have more autonomy in investment attraction, tax policy formulation, and are more conducive to the development of policies suitable for low-carbon development, which in turn promotes further reduction of carbon emissions in the process of urban scale expansion (Ahrend et al., 2017; Aryal et al., 2018). Second, cities with high administrative level have an advantage in fiscal decentralization within the region, in terms of both spending and freedom of finance, which leads to larger government investment in urban development and makes it easier to leverage the contribution of urban expansion to low-carbon development. (Zhou et al., 2013b; Ge et al., 2017).

Accompanied by the accelerating urbanization process and the continuous expansion of the city scale, the polycentric spatial strategy has gradually become a development concept advocated by some scholars. Spatial structure of polycentric cities can help to save transportation and commuting costs, reduce the energy consumption of urban building operations and production activities, make the flow and exchange of capital, logistics and information across regions more rapid and convenient promote local carbon emission reduction. In addition, it can also accelerate carbon emission reduction in the surrounding areas through positive demonstration effects of emission reduction, knowledge and technology spillover effects (Brezzi and Veneri, 2015; Guo et al., 2019).

By the end of 2020, 94.7% of China's cities with a population of 1 million or more will be covered by high-speed railroads. High-speed rail breaks down obstacles caused by spatial and temporal distance (Chen and Haynes, 2017), which makes the flow and exchange of capital, logistics and information across regions more rapid and convenient promote local carbon emission reduction, thereby contributing to low-carbon development. In addition, the improvement of transportation has promoted rapid cross regional population mobility, and knowledge exchange and interaction between different entities have accelerated carbon reduction in surrounding areas (Huang and Wang, 2020).

6 Conclusion and policy recommendations

With rapid urbanization and increasing greenhouse effect, low-carbon development is the integral factor of achieving sustainable development. We constructed a comprehensive analytical framework to quantify the impact of urban scale on low-carbon development and conducted an empirical study in 265 cities in China from 2009 to 2019. The results show that: first, urban scale can significantly contribute to low-carbon development and this finding holds after robustness tests; Specifically, for every 1% increase in urban scale, the low-carbon development level of the urban increases by 0.128%; second, urban scale contributes to low-carbon development mainly through three paths: efficiency improvement, industrial structure upgrading, and innovation; Third, there is heterogeneity in this effect across cities with different city levels, city structures, and different transportation conditions. Therefore, we make the following policy recommendations.

First, play the role of city scale in low-carbon development. Actively expand the scale of urban, reduce restrictions on the expansion of large cities appropriately to ensure sustainable development, play the leading role of central cities in urban clusters and metropolitan areas. Focus on the urbanization development of small and medium-sized cities, actively encourage the migration of rural population, improve their scale level and continuously enhance the positive externalities of low-carbon development.

Second, raise the environmental access threshold for new industries and guide industries to optimize and upgrade in the advanced direction to promote low-carbon development. Fully utilize the opportunities of rapid development of digital and intelligent technologies under the background of new urbanization, promote the deep integration of digital and intelligent technologies with urban form, and maximize the carbon reduction effect of technological innovation.

Third, different cities should make policies in line with their own low-carbon development according to local conditions. Based on the city's resource endowment, formulate preferential tax policies. Promote the diversified development of industries within the city, fully consider industry heterogeneity, and formulate differentiated industry innovation policies. Promote the clustering of high-tech enterprises, promote the perfect and efficient operation of public transportation and supporting infrastructure such as high-speed rail, reduce energy consumption caused by traffic congestion.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

RG: Data curation, Writing–original draft, Formal Analysis, Investigation, Software, Writing–review and editing. JuZ: Software, Writing–original draft, Supervision, Validation. XL: Data curation, Formal Analysis, Software, Writing–review and editing. JiZ: Conceptualization, Data curation, Methodology, Writing–original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Ahmad, A. L., Qi-JingNizami, Mannan, S. M., AbdulSaeed, and Sajjad, (2018). Carbon emission from deforestation, forest degradation and wood harvest in the temperate region of hindukush himalaya, Pakistan between 1994 and 2016. *Land Use Policy* 78, 781–790. doi:10.1016/j.landusepol.2018.07.009

Ahrend, R., Farchy, E., Kaplanis, I., and Lembcke, A. C. (2017). What makes cities more productive? evidence from five oecd countries on the role of urban governance. *J. Regional Sci.* 57 (3), 385–410. doi:10.1111/jors.12334

Ang, J. B. (2009). Co2 emissions, research and technology transfer in China. *MPRA Pap.* 68 (10), 2658–2665. doi:10.1016/j.ecolecon.2009.05.002

AryalMann, G. J., Loveridge, S., and Joshi, S. (2018). Exploring innovation creation across rural and urban firms: analysis of the national survey of business competitiveness. *J. Entrepreneursh. Public Policy* 7 (4), 357–376. doi:10.1108/jepp-d-18-00026

Au, C. C., and Henderson, J. V. (2006). *Are Chinese cities too small.* Oxford, United Kingdom: Oxford University Press.

Bai, Y., Deng, X., Jiang, S., Zhang, Q., and Wang, Z. (2017). Exploring the relationship between urbanization and urban eco-efficiency: evidence from prefecture-level cities in China. *J. Clean. Prod.* 195, 1487–1496. S0959652617327889. doi:10.1016/j.jclepro.2017.11.115

Bereitschaft, B., and Debbage, K. (2013). Urban form, air pollution, and co2 emissions in large u.s. metropolitan areas. *Prof. Geogr.* 65 (4), 612–635. doi:10.1080/00330124.2013.799991

Bettencourt, L. M., Lobo, J., Helbing, D., Kühnert, C., and West, G. B. (2007). Growth, innovation, scaling, and the pace of life in cities. *Proc. Natl. Acad. Sci. U. S. A.* 104, 7301–7306. doi:10.1073/pnas.0610172104

Brezzi, M., and Veneri, P. (2014). Assessing polycentric urban systems in the oecd: country, regional and metropolitan perspectives. *Eur. Plan. Stud.* 23 (6), 1128–1145. doi:10.1080/09654313.2014.905005

Brown, M. A., and Southworth, F. (2008). Mitigating climate change through green buildings and smart growth. *Environ. Plan. A* 40 (3), 653–675. doi:10.1068/a38419

Burnett, P. (2016). Overpopulation, optimal city size and the efficiency of urban sprawl. *Rev. Urban Regional Dev. Stud.* 28, 143–161. doi:10.1111/rurd.12051

Change, I. C. (2007). *Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change.* Geneva, Switzerland: IPCC.

Chen, Z., and Haynes, K. E. (2017). Impact of high-speed rail on regional economic disparity in China. *J. Transp. Geogr.* 65 (dec), 80–91. doi:10.1016/j.jtrangeo.2017.08.003

Cheng, Z., Li, L., and Liu, J. (2017a). Industrial structure, technical progress and carbon intensity in China's provinces. *Renew. Sustain. Energy Rev.*, 81(2), 2935–2946. doi:10.1016/j.rser.2017.06.103

Cheng, Z., Li, L., and Liu, J. (2017b). Industrial structure, technical progress and carbon intensity in China's provinces. *Renew. Sustain. Energy Rev.* 81 (pt.2), 2935–2946. doi:10.1016/j.rser.2017.06.103

China (2015). *Enhanced actions on climate change: China's intended nationally determined contributions.*

Chuai, X., and Feng, J. (2019). High resolution carbon emissions simulation and spatial heterogeneity analysis based on big data in nanjing city, China. *Sci. Total Environ.* 686 (10), 828–837. doi:10.1016/j.scitotenv.2019.05.138

Desmet, K., and Rossi-Hansbergh, E. (2013). Urban accounting and welfare. *Am. Econ. Rev.* 103, 2296–2327. doi:10.1257/aer.103.6.2296

Dhakal, S. (2009). Urban energy use and carbon emissions from cities in China and policy implications. *Energy Policy* 37 (11), 4208–4219. doi:10.1016/j.enpol.2009.05.020

Dong, F., Yu, B., Hadachin, T., Dai, Y., Wang, Y., Zhang, S., et al. (2018). Drivers of carbon emission intensity change in China. *Resour. Conservation Recycl.* 129, 187–201. doi:10.1016/j.resconrec.2017.10.035

Dong, X., Zheng, S., and Kahn, M. E. (2019). The role of transportation speed in facilitating high skilled teamwork across cities. *J. Urban Econ.* 115, 103212. doi:10.1016/j.jue.2019.103212

Düben, C., and Krause, M. (2020). Population, light, and the size distribution of cities. *J. Regional Sci.* 61, 189–211. doi:10.1111/jors.12507

Duncan, B., and Vernon, H. (1999). A theory of urban growth. *J. Political Econ.* 107 (2), 252–284. doi:10.1086/250060

Fan, J. P. H., Wong, T. J., and Zhang, T. (2007). Politically connected ceos, corporate governance, and post-ipo performance of China's newly partially privatized firms. *J. Financial Econ.* 84, 330–357. doi:10.1016/j.jfineco.2006.03.008

Fragkias, M., Lobo, J., Strumsky, D., and Seto, K. C. (2013). Does size matter? scaling of co2 emissions and us urban areas. *PLOS ONE* 8, e64727. doi:10.1371/journal.pone.0064727

Ge, J., Stanley, L. J., Eddleston, K., and Kellermanns, F. W. (2017). Institutional deterioration and entrepreneurial investment: the role of political connections. *J. Bus. Ventur.* 32 (4), 405–419. doi:10.1016/j.jbusvent.2017.04.002

Glaeser, E. L., and Kahn, M. E. (2010). The greenness of cities: carbon dioxide emissions and urban development. *NBER Work. Pap.* 67 (3), 404–418. doi:10.1016/j.jue.2009.11.006

Gottdiener, M., Budd, L., and Lehtovuori, P. (2005). *Key concepts in urban studies*. Thousand Oaks, California, United States: SAGE.

Guo, L., Luo, J., Yuan, M., Huang, Y., Shen, H., and Li, T. (2019). The influence of urban planning factors on pm 2.5 pollution exposure and implications: a case study in China based on remote sensing, lbs, and gis data. *Sci. Total Environ.* 659, 1585–1596. doi:10.1016/j.scitotenv.2018.12.448

Huang, Y., and Wang, Y. (2020). How does high-speed railway affect green innovation efficiency? a perspective of innovation factor mobility - sciencedirect. *J. Clean. Prod.* 265, 121623. doi:10.1016/j.jclepro.2020.121623

Huo, T., Xu, L., Feng, W., Cai, W., and Liu, B. (2021). Dynamic scenario simulations of carbon emission peak in China's city-scale urban residential building sector through 2050. *Energy Policy* 159, 112612. doi:10.1016/j.enpol.2021.112612

Jia, J., Fan, Y., and Guo, X. (2012). The low carbon development (lcd) levels' evaluation of the world's 47 countries (areas) by combining the fahp with the topsis method. *Expert Syst. Appl.* 39 (7), 6628–6640. doi:10.1016/j.eswa.2011.12.039

Jia, J., Xin, L., Lu, C., Wu, B., and Zhong, Y. (2023). China's CO2 emissions: a systematical decomposition concurrently from multi-sectors and multi-stages since 1980 by an extended logarithmic mean divisia index. *Energy Strategy Rev.* 49, 101141. doi:10.1016/j.esr.2023.101141

Jiang, D. (2022). Transformation and development of the coal-based energy industry under the goals of carbon peaking and carbon neutrality. *Chin. J. Urban Environ. Stud.* 10 (02). doi:10.1142/s2345748122500087

Joshua, D., and Edward, F. (2015). Regional industrial structure and agglomeration economies: an analysis of productivity in three manufacturing industries. *Regional Sci. Urban Econ.* 42 (1–2), 1–14. doi:10.1016/j.regsciurbeco.2011.04.006

Kennedy, C., Steinberger, J., Gasson, B., Hansen, Y., Hillman, T., Havranek, M., et al. (2010). Methodology for inventorying greenhouse gas emissions from global cities. *Energy Policy* 38 (9), 4828–4837. doi:10.1016/j.enpol.2009.08.050

Kuang, B., Lu, X., Zhou, M., and Chen, D. (2020). Provincial cultivated land use efficiency in China: empirical analysis based on the sbm-dea model with carbon emissions considered. *Technol. Forecast. Soc. Change* 151, 119874. doi:10.1016/j.techfore.2019.119874

Leo, S. (1975). The productivity of cities. *Q. J. Econ.* 89, 393. doi:10.2307/1885259

Li, K., and Lin, B. (2009). Heterogeneity analysis of the effects of technology progress on carbon intensity in China. *Int. J. Clim. Change Strategies Manag.* 8, 129–152. doi:10.1108/ijccsm-05-2015-0053

Li, R., Wang, Q., Liu, Y., and Jiang, R. (2021). Per-capita carbon emissions in 147 countries: the effect of economic, energy, social, and trade structural changes. *Sustain. Prod. Consum.* 27 (8), 1149–1164. doi:10.1016/j.spc.2021.02.031

Li, W., Sun, W., Li, G., Cui, P., Wu, W., and Jin, B. (2017). Temporal and spatial heterogeneity of carbon intensity in China's construction industry. *Resour. Conservation Recycl.* 126, 162–173. doi:10.1016/j.resconrec.2017.07.043

Li, C. (2021). The impact of industrial structure upgrading on my country's carbon emission reduction from the perspective of high-quality development. *Sustain. Dev.* 11 (1), 149–159. doi:10.12677/sd.2021.111018

Liu, J., Li, M., and Ding, Y. (2021). Econometric analysis of the impact of the urban population size on carbon dioxide (CO2) emissions in China. *Environ. Dev. Sustain.* 23, 18186–18203. doi:10.1007/s10668-021-01433-w

Liu, Z., Wang, F., Tang, Z., and Tang, J. (2019). Predictions and driving factors of production-based co2 emissions in beijing, China. *Sustain. Cities Soc.* 53, 101909. doi:10.1016/j.scs.2019.101909

Luo, D., Tong, N., and She, G. (2017). Citylevel political uncertainty and citylevel ipo activities. *Account. Finance* 57, 1447–1480. doi:10.1111/acfi.12341

Martine, G. (2009). Population dynamics and policies in the context of global climate change. *Iied Unfpa*.

Melo, P. C., Graham, D. J., and Noland, R. B. (2009). A meta-analysis of estimates of urban agglomeration economies. *Regional Sci. Urban Econ.* 39 (3), 332–342. doi:10.1016/j.regsciurbeco.2008.12.002

Mizobuchi, K. (2008). An empirical study on the rebound effect considering capital costs. *Energy Econ.* 30 (5), 2486–2516. doi:10.1016/j.eneco.2008.01.001

Murtaugh, P. A., and Schlax, M. G. (2009). Reproduction and the carbon legacies of individuals. *Glob. Environ. Change* 19 (1), 14–20. doi:10.1016/j.gloenvcha.2008.10.007

Nan, Z., Nina, K., Wei, F., Ke, J., and Levine, M. (2018). Scenarios of energy efficiency and co 2 emissions reduction potential in the buildings sector in China to year 2050. *Nat. Energy* 3, 978–984. doi:10.1038/s41560-018-0253-6

Nejat, P., Jomehzadeh, F., Taheri, M. M., Gohari, M., and Majid, M. A. (2015). A global review of energy consumption, co2 emissions and policy in the residential sector (with an overview of the top ten co2 emitting countries). *Renew. Sustain. Energy Rev.* 43, 843–862. doi:10.1016/j.rser.2014.11.066

Payne, J. E. (2010). Survey of the international evidence on the causal relationship between energy consumption and growth. *J. Econ. Stud.* 37 (1), 53–95. doi:10.1108/01443581011012261

Peters, G. P., Marland, G., Quéré, C. L., Boden, T., Canadell, J. G., and Raupach, M. R. (2012). Rapid growth in co2 emissions after the 2008-2009 global financial crisis. *Nat. Clim. Change* 2 (1), 2–4. doi:10.1038/nclimate1332

Ray, S. C., and Desli, E. (1997). Productivity growth, technical progress, and efficiency change in industrialized countries: comment. *Am. Econ. Rev.* 87 (5), 1033–1039.

Rosenthal, S. S., and Strange, W. C. (2006). Evidence on the nature and sources of agglomeration economies. *Handb. Regional Urban Econ.* 4. doi:10.1002/9780470996225

Satterthwaite, D. (2008). Cities' contribution to global warming: notes on the allocation of greenhouse gas emissions. *Environ. Urbanization* 20 (2), 539–549. doi:10.1177/0956247808096127

Satterthwaite, D. (2009). The implications of population growth and urbanization for climate change. *Environ. Urbanization* 21 (2), 545–567. doi:10.1177/0956247809344361

Shim, G. E., Rhee, S. M., Ahn, K. H., and Chung, S. B. (2006). The relationship between the characteristics of transportation energy consumption and urban form. *Ann. Regional Sci.* 40, 351–367. doi:10.1007/s00168-005-0051-5

Smil, V. (2008). *Energy in nature and society:general energetics of complex Systems*. Cambridge, Massachusetts, United States: MIT Press.

Sueyoshi, T., Li, A., and Liu, X. (2019). Exploring sources of China's CO2 emission: decomposition analysis under different technology changes. *Eur. J. Operational Res.* 279 (3), 984–995. doi:10.1016/j.ejor.2019.06.037

Sun, M., Yuan, Y., Zhang, J., Wang, R., and Wang, Y. (2014). Greenhouse gas emissions estimation and ways to mitigate emissions in the yellow river delta high-efficient eco-economic zone, China. *J. Clean. Prod.* 81 (15), 89–102. doi:10.1016/j.jclepro.2014.06.032

Tian, X., Bai, F., Jia, J., Liu, Y., and Shi, F. (2019). Realizing low-carbon development in a developing and industrializing region: impacts of industrial structure change on CO2 emissions in southwest China. *J. Environ. Manag.* 233 (1), 728–738. doi:10.1016/j.jenvman.2018.11.078

Wang, D. D. (2019). Performance assessment of major global cities by dea and malmquist index analysis. *Comput. Environ. Urban Syst.* 77 (4), 101365. doi:10.1016/j.compenvurbsys.2019.101365

Wang, L., Zhao, Z., Xue, X., and Wang, Y. (2019). Spillover effects of railway and road on co2 emission in China: aspatiotemporal analysis. *J. Clean. Prod.* 234, 797–809. doi:10.1016/j.jclepro.2019.06.278

Wang, S. J., and Huang, Y. Y. (2019). Spatial spillover effect and driving forces of carbon emission intensity at city level in China. *Acta Geogr. Sin.* 74 (6), 1131–1148. doi:10.1007/s11442-019-1594-1

Wei, H. A., and Yf, B. (2020). City size and energy conservation: do large cities in China consume more energy? *Energy Econ.* 92, 104943. doi:10.1016/j.eneco.2020.104943

Wei, W., Zhang, X., Zhou, L., Xie, B., Zhou, J., and Li, C. (2021). How does spatiotemporal variations and impact factors in co_2 emissions differ across cities in China? investigation on grid scale and geographic detection method. *J. Clean. Prod.* (25), 321. doi:10.1016/j.jclepro.2021.128933

Xia, C., Li, Y., Xu, T., Ye, Y., Shi, Z., Peng, Y., et al. (2018). Quantifying the spatial patterns of urban carbon metabolism: a case study of hangzhou, China. *Ecol. Indic.* 95P1, 474–484. doi:10.1016/j.ecolind.2018.07.053

Xia, C., Xiang, M., Fang, K., Li, Y., Liu, J., Shi, Z., et al. (2020). Spatial-temporal distribution of carbon emissions by daily travel and its response to urban form: a case study of hangzhou, China. *J. Clean. Prod.* 257, 120797. doi:10.1016/j.jclepro.2020.120797

Xu, Q., Dong, Y. X., and Yang, R. (2018). Urbanization impact on carbon emissions in the pearl river delta region: kuznets curve relationships. *J. Clean. Prod.* 180, 514–523. doi:10.1016/j.jclepro.2018.01.194

Xu, Z. S., and Xu, Y. M. (2021). Study on the spatio-temporal evolution of the Yangtze River Delta urban agglomeration by integrating Dmsp/Ols and Npp/Viirs nighttime light data. *J. Geo-information Sci.* 23 (5), 837–671.

Yang, Y., Cai, W., and Wang, C. (2014). Industrial co2 intensity, indigenous innovation and r&d spillovers in China's provinces. *Appl. Energy* 131 (131), 117–127. doi:10.1016/j.apenergy.2014.06.033

Yang, Y., Jia, J., Devlin, A. T., ZhouXie, Y. D., and Ju, M. (2020). Decoupling and decomposition analysis of residential energy consumption from economic growth during 2000–2017: a comparative study of urban and rural guangdong, China. *Energies* 13, 4461. doi:10.3390/en13174461

Yu, X., Wu, Z., Zheng, H., Li, M., and Tan, T. (2020). How urban agglomeration improve the emission efficiency ? a spatial econometric analysis of the yangtze river delta urban agglomeration in China. *J. Environ. Manag.* 260 (15), 110061–110068. doi:10.1016/j.jenvman.2019.110061

Zhang, Y. J., LiuZhang, Z. H., and Tan, T. D. (2014). The impact of economic growth, industrial structure and urbanization on carbon emission intensity in China. *Nat. Hazards* 73 (2), 579–595. doi:10.1007/s11069-014-1091-x

Zhao, J., Chen, Y., Ji, G., and Wang, Z. (2018). Residential carbon dioxide emissions at the urban scale for county-level cities in China: a comparative study of nighttime light data. *J. Clean. Prod.* 180 (10), 198–209. doi:10.1016/j.jclepro.2018.01.131

Zhao, X., Burnett, J. W., and Fletcher, J. J. (2014). Spatial analysis of China province-level CO2 emission intensity. *Renew. Sustain. Energy Rev.* 33 (2), 1–10. doi:10.1016/j.rser.2014.01.060

Zhou, C., Wang, S., and Wang, J. (2019). Examining the influences of urbanization on carbon dioxide emissions in the yangtze river delta, China: kuznets curve relationship. *Sci. Total Environ.* 675 (20), 472–482. doi:10.1016/j.scitotenv.2019.04.269

Zhou, N., Fridley, D., Khanna, N. Z., Ke, J., Mcneil, M., and Levine, M. (2013a). China's energy and emissions outlook to 2050: perspectives from bottom-up energy end-use model. *Energy Policy* 53, 51–62. doi:10.1016/j.enpol.2012.09.065

Zhou, X., Jie, Z., and Li, J. (2013b). Industrial structural transformation and carbon dioxide emissions in China. *Energy Policy* 57, 43–51. doi:10.1016/j.enpol.2012.07.017

Zhou, Y., and Liu, Y. (2016). Does population have a larger impact on carbon dioxide emissions than income? evidence from a cross-regional panel analysis in China. *Appl. Energy* 180, 800–809. doi:10.1016/j.apenergy.2016.08.035