



Impact of population agglomeration in big cities on carbon emissions

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Abstract

The study explored the influencing mechanism of population agglomeration in large cities on carbon emissions, including technological innovation, industrial structure, and transportation effects. Moreover, we attempt to explore the nonlinear impact of population agglomeration in large cities on carbon emissions. We used the panel data of 207 big cities with a permanent resident population of more than 1 million to study the relationship between population agglomeration and carbon emissions. We found that population agglomeration to big cities increased urban carbon emissions significantly. The results of the mechanism analysis showed that population agglomeration to big cities raised carbon emissions by the channel of industrial structure and transportation effects. The channel of technological innovation effect decreased carbon emissions but did not offset the growth of carbon emissions caused by industrial structure and transportation effects. Nonlinear estimation findings demonstrated that the impact of population agglomeration on carbon emissions was different in big cities with varying levels of population.

Keywords Seventh national census · Population agglomeration · Carbon emission · Carbon neutrality

Introduction

At the end of 2020, China's urbanization rate has exceeded 60%. In addition, the population of China's megacities continues to grow, and the trend of population agglomeration in big cities is evident. According to the data of the seventh national census, 18 cities already have more than 10 million permanent resident population, namely, Beijing, Shanghai, Chongqing, Chengdu, Shenzhen, Guangzhou, Tianjin, Dongguan, Hangzhou, Zhengzhou, Suzhou, Wuhan, Changsha, Harbin, Xi'an, Shijiazhuang, Qingdao, and Linyi. Among them, the permanent resident population of Beijing, Shanghai, Chongqing, and Chengdu has exceeded 20 million. However, in the sixth national census in 2010, only 11 cities have a permanent resident population of more than 10 million. The data of the seventh national census revealed

that 73 cities have a permanent population of 5–10 million. Compared with the sixth national census data in 2010, some large cities, such as Shenzhen, have shown a strong population growth momentum—a massive increase of 7.2 million in population, as shown in Fig. 1. The agglomeration of the population to big cities has become a trend. However, notably, cities, which account for only 2% of the world's area, consume 75% of global energy.¹

Since the reform and opening-up, urbanization and population agglomeration have become important engines for economic growth. Although the population agglomeration and economic growth in big cities are advancing with leaps and bounds, carbon dioxide emissions in big cities continue to grow, and the greenhouse effect exists (Fig. 2). Intuitively, people tend to think that urban population expansion leads to environmental pollution and other urban diseases. So is it an empirical fact that population concentration leads to a continuous increase in carbon emissions in large cities?

Therefore, does population agglomeration lead to a continuous increase in carbon emissions in big cities? China's economy was in transition from rapid growth to high-quality growth. Moreover, the Chinese government has always attached great importance to ecological civilization.

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Specifically, the Constitutional Amendment passed by the Two Sessions (the National People's Congress and the Chinese People's Political Consultative Conference) in 2018 included "beautiful China" and ecological civilization into the Constitution. Furthermore, President Xi Jinping announced the goal of China's "carbon emission peak" and "carbon neutrality" to the world at the 75th UN General Assembly in 2020. In this context, studying the impact of population agglomeration in large cities and its mechanism on carbon emissions is not only of theoretical significance but also of practical value. This study uses panel data of 207 large cities with more than 1 million permanent resident population to explore the relationship between population agglomeration and carbon dioxide emissions. Benchmark regression and instrumental variable estimation find that population agglomeration in large cities significantly increases urban carbon dioxide emissions. Mechanism analysis finds that the agglomeration of the population in big cities aggravated carbon emissions mainly through industrial structure and transportation effects. Nonlinear estimation finds that with the increase of the permanent resident population in big cities, the growth of carbon dioxide emissions initially increases and then decreases. We also find an inverted U-shaped relationship between the permanent resident population of large cities and carbon emissions.

Two groups of articles are closely related to this paper. One group of articles focus on the impact of population agglomeration on air quality. One of the views is that population concentration deteriorates air quality, such as increasing SO₂ emissions (Wu 2010), carbon emissions (Qu and Jiang 2012), urban air quality index (Wang et al. 2015), PM_{2.5} concentration (Shao et al. 2019; Gan et al. 2021), and industrial pollutants (He 2019). Liu et al. (2019) find that a causal relationship exists between population agglomeration and environmental pollution. Overpopulation concentration produces a large amount of garbage. Moreover, once the output of garbage exceeds the self-purification capacity of the ecological environment, environmental pollution increases (Li and Fu 2016). Therefore, the high productivity brought by population agglomeration in big cities at the cost of environmental pollution and other urban diseases may eventually lead to a decline in people's welfare (Zhou and Li 2010; Oliveira et al. 2014).

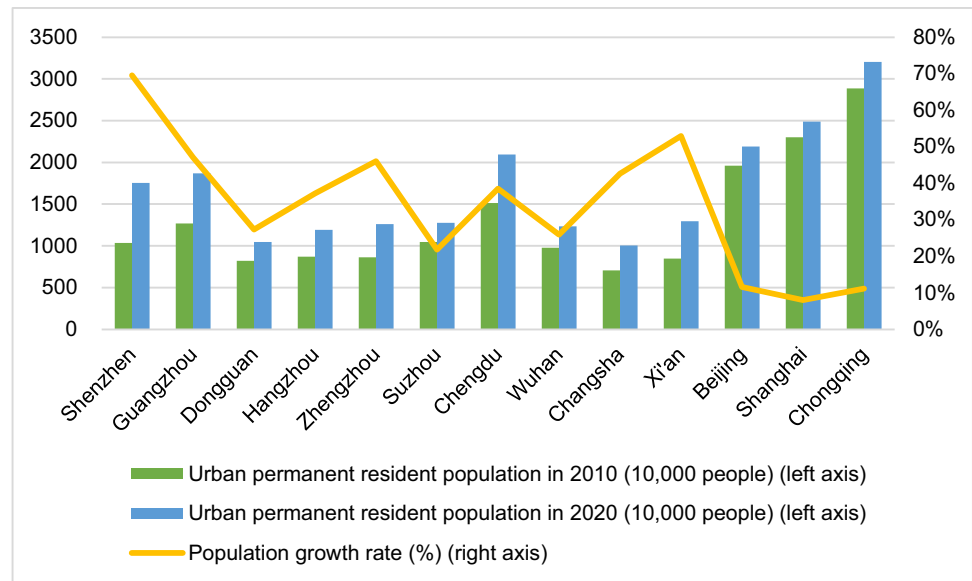
Another view is that population concentration improves air quality (Liu and Song 2013; Li and Zhang 2013). Some scholars pointed out that agglomeration is beneficial to reduce environmental pollution because the discharge of pollutants has economies of scale (Lu and Feng 2014; Zheng and Lu 2018). Namely, the economy of scale brought by the population agglomeration is conducive to reducing the overall pollution emissions (Cole and Neumayer 2004; Hankey and Marshall 2010). Fang and Tao (2017) found that there

does exist win-win situations in which population agglomeration increases while the environmental quality improves. Secondly, population agglomeration accelerates the speed of industrial transformation (Yang et al. 2021). Population agglomeration also helps to form a cleaner industrial structure by increasing the proportion of the service industry (Arrow et al. 1995). Moreover, population concentration promotes technological innovation and generates positive externalities. Therefore, positive externality improves green technology innovation (Arrow et al. 1995; Andreoni and Levinson 2001), which ultimately reduces the cost of pollution (Shefer 1973; Romer 1986). In addition, the demand for private cars is reduced by compact and high-density urban spacial structure (Hong 2017). With the growth of public transportation, thereby reducing urban traffic carbon emissions (Glaeser and Resseger 2010; Timmons et al. 2016). In the study of four Chinese megacities, Wang et al. (2017) found that transportation factors were found to have significant negative effects on CO₂ emission.

The third view is that a nonlinear relationship exists between population agglomeration and air pollution (Xu and Yang 2017; Liu and Leng 2020). Wang and Zhou (2013) found that population size has no significant correlation with environment pollutions and the growth of population does not cause environment pollution. Scholars (Li and Ma 2017; Yang et al. 2020) hold that an "inverted U-shaped" relationship exists between population agglomeration and environmental pollution. Other scholars argued that population agglomeration increases pollution emissions, and they claimed a right "N" environmental Kuznets curve (Tao and Peng 2017). Based on the samples of prefecture-level cities in China, Li et al. (2022) used a spatial lag model to verify the relationship between urban population agglomeration and haze pollution and found a significant "N-type" nonlinear relationship.

Another group of articles focuses on the impact of urbanization on carbon emissions. Related research includes two viewpoints. Most studies believed that urbanization has increased carbon emissions (Parikh and Shukla 1995; Sun et al. 2022). Poumanyong and Kaneko (2010) employed the STIRPAT model and panel data of 99 countries to investigate the relationship between urbanization and carbon emissions. They argued that the impact of urbanization on emissions is positive for all the countries, but it is more pronounced in the middle-income countries than in the other countries. Al-Mulali et al. (2012) indicated that most countries have a positive long-run relationship between urbanization and CO₂ emission. Moreover, other studies from samples of China (Song and Xu 2011; Chen et al. 2020), sub-Saharan Africa (Hanif 2018), the top ten carbon emitters (Nejat et al. 2015), and the European Union (Kasman and Duman 2015) have drawn similar conclusions. Some scholars hold that

Fig. 1 Population data of the sixth and seventh national census in major cities. Data source: China Statistics Bureau



a negative relationship exists between urbanization and carbon emissions (Liddle 2004; Fan et al. 2006). Lv et al. (2019) suggested that urbanization has a significant negative impact on railway and waterway transport carbon emissions in China. In addition, Wang et al. (2021) examined the relationship between urbanization rate and carbon dioxide emissions in OECD countries by using the dynamic panel autoregressive distribution lag (ARDL) model. Their results indicate that there is a negative impact of urbanization on carbon emissions in developed countries.

From the above articles, we can find that the research on the impact of population agglomeration on environmental pollution has achieved fruitful research results. However, the main pollutants in previous literature are haze, nitrogen oxides, SO₂, and others; few studies concerned about

CO₂. Most scholars used registered population to measure urbanization. However, China's population agglomeration cannot be truly reflected by registered population (Shao et al. 2019). In addition, cities include large cities, small cities, and medium-sized cities. While few studies used large cities as samples.

Specifically, research on identifying the influencing mechanism of population agglomeration on carbon emissions is limited. Moreover, studies on practical countermeasures for China to achieve energy conservation and carbon emissions reduction in the context of population agglomeration in large cities are scarce. Therefore, this article studies the impact of population agglomeration in large cities on carbon emissions.

Fig. 2 China's carbon emissions (2000–2019). Data source: CEADs

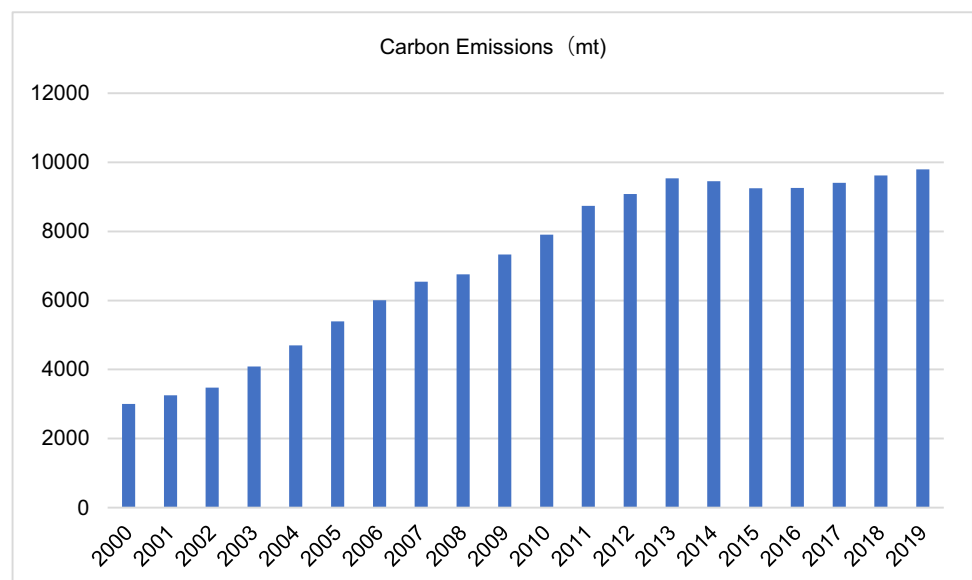


Table 1 Variable statistical description

Variable	Mean value	Standard deviation	Minimum value	Maximum value
Carbon emissions: million tons	20.81	22.955	1.138	214.267
Carbon emission intensity: ton/yuan	0.000438	0.0006282	0.0000225	0.008324
Urban permanent resident population: 10,000	280.36	258.42	100	2173
GDP per capita: yuan	56625.7	124107.8	3878	6421762
Energy efficiency: yuan/ton	5430.31	4797.69	178.83	58066.23
The added value of the secondary industry as a proportion of GDP: %	49.24	10.84	8.05	88.99
Economic openness: %	2.63	2.621	0.0000358	2.265

In summary, the innovations of this article are mainly reflected in the following. First, this paper explored the influencing mechanism of population agglomeration in large cities on carbon emissions, including technological innovation, industrial structure, and transportation effects. Moreover, the study attempts to explore the nonlinear impact of population agglomeration in large cities on carbon emissions to provide practical CO₂ reduction policies. Second, this article uses the large cities with more than 1 million permanent resident population as the research sample for the first time to examine the impact of large cities' population agglomeration on carbon emissions. Third, owing to the availability of data, current empirical studies on carbon emissions in China mostly use time-series data or provincial panel data, whereas urban carbon emissions data are rarely used for research. This study uses the urban carbon dioxide data from the China Emission Accounts and Datasets.

Model and data

Based on the STIRPAT model and EKC hypothesis, this study establishes the following benchmark model to study the impact of population agglomeration in large cities on carbon emissions:

$$\ln I_{it} = \beta_0 + \beta_1 \ln P_{it} + \beta_2 \ln A_{it} + \beta_3 \ln T_{it} + \beta_4 \ln X_{it} + e_{it} \quad (1)$$

In Eq. (1), I , P , A , and T are carbon dioxide emissions, population size, wealth per capita, and technology level, respectively, X refers to other control variables, and e_{it} indicates the random error term. Subscript i represents the unit of the city, and t represents time. The indicators to measure the variables in Eq. (1) are explained as follows:

- (1) Urban carbon emissions (I). Urban carbon dioxide emissions are the explained variable in this article. Data comes from China Emission Accounts and Datasets.
- (2) Urban permanent resident population (P). This variable is the core explanatory variable, which is measured by the city's permanent resident population to indicate the level of population agglomeration in the city. The permanent resident population data of each city come from the statistical yearbooks.
- (3) GDP per capita (gdp). Wealth per person is usually characterized by GDP per capita and converted to the actual value of GDP per capita (last year = 100). To verify the classic EKC hypothesis, the quadratic term of GDP per capita was added to the model to examine the relationship between economic growth and carbon emissions. Data comes from the Statistics Database of China Economic Network.
- (4) Technical level (T). Technological innovation is an important way to control air pollution. This article uses energy efficiency to express technological innovation according to Shao et al. (2019). Energy efficiency is expressed by the actual value of GDP per unit of energy (last year = 100). Data comes from China Energy Statistical Yearbook and China Statistical Yearbook.
- (5) Economic openness. Economic opening is one of the important factors affecting environmental quality. To test the "pollution paradise" hypothesis, this study uses FDI/GDP to measure the degree of openness. Data comes from Statistics Database of China Economic Network.

The sample of this article is composed of panel data of 207 large cities with an urban permanent resident population of more than 1 million people from 2005 to 2018. Table 1 shows the descriptive statistics of the variables.

Table 2 Population agglomeration and carbon emissions in big cities

Model description	(1) Carbon emissions Benchmark regression	(2) Carbon emissions Benchmark regression	(3) Carbon emissions Replace core variables	(4) Carbon emissions Replace core variables	(5) Carbon emission intensity Replace-dependent variable	(6) Carbon emission intensity Replace-dependent variable
Urban permanent resident population	0.0529* (0.0272)				0.0791*** (0.0265)	
Urban permanent resident population in the lag period		0.0504** (0.0205)				0.0700*** (0.0251)
Residential density			0.0129** (0.00624)			
Residential density in the lag period				0.0111* (0.00624)		
GDP per capita	0.721*** (0.205)	0.794*** (0.211)	0.751*** (0.888)	0.814*** (0.193)	-0.044 (0.197)	-0.0472 (0.209)
Quadratic of GDP per capita	-0.0110 (0.00980)	-0.0145 (0.00979)	-0.011 (0.009)	-0.0138* (0.009)	-0.0145 (0.0093)	-0.0174* (0.00922)
Energy efficiency	-0.0553*** (0.0144)	-0.0617*** (0.0143)	-0.0525*** (0.0144)	-0.0599*** (0.0144)	-0.0603*** (0.0145)	-0.0655*** (0.0143)
Economic openness	-0.284 (0.231)	-0.247 (0.249)	-0.257 (0.229)	-0.227 (0.244)	-0.0916 (0.225)	-0.105 (0.240)
Constant term	-4.054*** (1.131)	-3.99*** (1.179)	-3.74*** (1.11)	-3.96*** (1.145)	-5.85*** (1.145)	-5.97*** (1.2)
Urban-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
N	2659	2462	2634	2438	2659	2462
A-R ²	0.883	0.853	0.881	0.851	0.906	0.908

The brackets are the robust standard deviations. *, **, and *** indicate significant at the 10%, 5%, and 1% levels, respectively. This also applies to the following table

Impact of population agglomeration in big cities on carbon emissions and influencing mechanism

Benchmark regression

Table 2 shows the benchmark empirical results and robustness test results. The first column shows the regression results of the fixed-effect model. After controlling the urban and year fixed effects, the urban permanent resident population is significantly positively correlated with carbon dioxide emissions: the urban permanent resident population increases by 1%, and the urban carbon emissions increase by 0.0529%.

In the second column, the urban permanent resident population is lagged by one period. The results show that the positive correlation between carbon dioxide emissions and the urban permanent resident population in the lag period is still significant. The urban permanent resident population in the lag period increases by 1%, and urban carbon emissions increase by 0.0504%.

The results of the benchmark model show that population agglomeration in large cities has significantly increased carbon dioxide emissions. In the current period, the urban permanent population increases by 1%, and carbon dioxide emissions increase by 0.0529%. The urban permanent population in the lag period increases by 1%, and carbon dioxide emissions increase by 0.0504%.

Robustness Test

First, we replace the core explanatory variable with residential density. Residential density is an important indicator of urban population agglomeration, which is the ratio of urban permanent resident population to residential land. The data come from the China City Yearbook and China City Construction Yearbook. Column (3) shows the robustness test results replacing the core explanatory variable with residential density. Column (3) shows that after controlling the year-fixed effect, the urban-fixed effect, and a series of control variables, a significant positive correlation exists between residential density and urban carbon emissions, with a 1% increase in residential density and a 0.0129% increase in carbon emissions. To alleviate the endogenous problem caused by reverse causal bias, the lagged one-period residential density is used as the core explanatory variable in column (4). The results show that the positive correlation between the lagged one-period residential density and carbon dioxide emissions is still significant.

Second, China implemented carbon intensity reduction in the early stage, so we replaced the dependent variable with urban carbon intensity for the robustness test. Urban carbon

Table 3 Population agglomeration and carbon emissions in big cities: regression results of the dynamic panel model

	The explained variable is CO ₂		
	(1)	(2)	(3)
	Pool OLS	SGMM	FE
Lag term of dependent variable	0.995*** (0.00157)	0.941*** (0.0192)	0.840*** (0.0273)
Urban permanent resident population	0.000882 (0.00239)	0.0672** (0.0331)	0.0114 (0.00713)
GDP per capita	0.000633 (0.00211)	-0.072*** (0.0204)	0.0850*** (0.0230)
Energy efficiency	-0.054*** (0.0186)	-0.033*** (0.011)	-0.061*** (0.0247)
Opening to the outside world	0.0377 (0.0319)	0.138 (0.195)	-0.0474 (0.0945)
Constant term	0.138*** (0.0226)	0.484*** (0.171)	-0.450** (0.209)
<i>N</i>	2460	2460	2460
<i>R</i> ²	0.998		
<i>AR</i> (1)		0.000	
<i>AR</i> (2)		0.123	
<i>Hansen test</i>		0.224	

Sangan’s test is invalid under heteroscedasticity; this article reports the results of Hansen’s test

intensity is the carbon dioxide emission per GDP. Columns 5 and 6 show the results of the robustness test. Consistent with the results of the benchmark regression, the urban permanent resident population and the lag urban permanent resident population are significantly positively correlated with carbon intensity. The urban permanent resident population increases by 1%, and the carbon intensity increases by 0.0791%; the lag urban permanent resident population increases by 1%, and the carbon intensity increases by 0.07%.

Therefore, the robustness test verifies the conclusion that population agglomeration in big cities increases carbon emissions. Our conclusion confirms the intuition that population concentration in big cities aggravates carbon emission. According to population carrying capacity theory, when population concentration exceeds certain environmental tolerance, environmental deterioration will be aggravated.

Dynamic panel model estimation

In view of the endogenous problems that may be caused by reverse causality and missing variables in the model, to control and alleviate this problem, we introduce the first-order lag term of the dependent variable in Eq. (1) and expand it into a dynamic panel model, as shown in Eq. (2):

$$\ln I_{it} = \beta_0 + \gamma \ln I_{it-1} + \beta_1 \ln P_{it} + \beta_2 \ln A_{it} + \beta_3 \ln T_{it} + \beta_4 \ln X_{it} + \eta_i + \alpha_t + e_{it} \quad (2)$$

Table 4 Test of the mechanism of population agglomeration in big cities on carbon emissions

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable	Technological innovation effect	Technological innovation effect	Industrial structure effect	Industrial structure effect	Transportation effect	Transportation effect
	Technological innovation	Technological innovation	Proportion of secondary production	Proportion of secondary production	Transportation	Transportation
Urban permanent resident population	0.00661*** (0.00229)		0.417** (0.204)		0.0156*** (0.0059)	
Urban permanent resident population in the lag period		0.00630*** (0.00223)		0.975*** (0.285)		0.0341** (0.0178)
Constant term	Yes	Yes	Yes	Yes	Yes	Yes
Control variable	Yes	Yes	Yes	Yes	Yes	Yes
Urban-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	2867	2666	2865	2665	2863	2666
<i>R</i> ²	0.203	0.174	0.400	0.417	0.922	0.922

We use the method of system generalized method of moment to estimate the above dynamic panel model, and Table 3 shows the estimation results. Column 2 is the estimated result of the system GMM with CO₂ as the dependent variable. The coefficients of the core explanatory variable urban permanent resident population and the dependent variable of the lag period are significantly positive. Moreover, to verify the reliability of the results of the system GMM model, the rationality of the model setting and the validity of the instrumental variables were tested. The *P* value of the second-order autoregressive test result is 0.123, that is, the null hypothesis is accepted at the 5% significance level. In addition, no second-order autocorrelation exists in the residual items after the difference. For the overidentification test, we use the Hansen test recommended by Chen (2013). The Hansen test results show that the null hypothesis could not be rejected at the 5% significance level, indicating that all instrumental variables are valid. In addition, according to the research of Nickell (1981) and Hsiao (1986), the upper and lower limits of the coefficients of the dependent variable for the lag term are determined by the pool OLS and FE estimates. Therefore, this article adds the first-order lag term of carbon emissions to the Pool OLS model and the fixed-effects model for estimation. Columns 1 and 3 of Table 3 show the estimation results. We found that the coefficient estimate (0.941) of the first-order lag term of the dependent variable CO₂ in the SGMM model is exactly between 0.995 and 0.84. Therefore, we believe that the model of the system GMM is reasonable. From the estimated results in column 2, the urban permanent resident population has a significant positive impact on carbon emissions, which is consistent with the estimated results in Table 2. That is,

the increase in the urban permanent population leads to a significant increase in carbon dioxide emissions, which proves once again that population concentration in big cities caused the urban disease of increasing carbon emissions. According to the theory of environmental carrying capacity, the growth rate of population should adapt to the natural environment; otherwise, it will harm the environment. In recent 10 years, the population growth in big cities has exceeded any previous historical period, but environmental pollution and other problems have followed.

Mechanism analysis

The above research results of benchmark regression, dynamic panel model estimation, and robustness test all show that population agglomeration in large cities has a positive impact on urban carbon emissions. Therefore, what is the influencing mechanism of population agglomeration in large cities on carbon emissions? In other words, how population agglomeration in big cities affects carbon emissions. Based on economic logic and literature research, this section studies the influencing mechanism of population agglomeration on carbon emissions from three aspects: technological innovation, industrial structure, and transportation effects. Table 4 reports the empirical results of the influencing mechanism.

First, the agglomeration of the population in big cities affects urban carbon emissions through technological innovation. On the one hand, technological progress is conducive to improving clean, green, and emission reduction technologies and ultimately achieves the result of reducing carbon emissions. On the other hand, population agglomeration has brought about knowledge and technology spillovers, thereby

Table 5 Population agglomeration and carbon emissions in big cities: estimation of instrumental variables

	(1)	(2)	(3)	(4)
First-stage regression	Urban permanent resident population	Residential density		
Land supply growth rate	−0.1288*** (0.0027)	−0.0084*** (0.0016)		
Other control variables	Yes			
<i>F</i> value of the first stage regression	170.89	347.59		
Second-stage regression		Carbon emissions		OLS
Urban permanent resident population	0.5543** (0.219)		0.6961*** (0.0853)	
Residential density		0.8285* (0.492)		0.02497*** (0.0071)
Land supply growth rate			−0.00049 (0.00033)	−0.0004 (0.0003)
Other control variables	Yes	Yes	Yes	Yes
Number of samples	2632	2608	2632	2608
<i>A-R</i> ²	0.5549	0.3970	0.9944	0.9943

promoting technological progress. To verify this mechanism, we select research and development (R&D) intensity to characterize the effect of technological progress. The research and development (R&D) intensity is measured by the proportion of R&D employees in the total number of employees. Columns 1 and 2 of Table 4 report the empirical results of the effects of technological progress. The coefficients of the permanent resident population in the cities in column (1) and its lag term in column (2) are significantly positive. This result indicates that, as the population gathers in big cities, opportunities for communication between people increase. Furthermore, the population concentration promotes the spillover of knowledge and technology and thus promotes technological innovation.

Second, population agglomeration in big cities can affect urban carbon emissions through the industrial structure. On the one hand, the industrial structure usually changes from a relatively clean agricultural industry to a highly polluted industrial structure and then to environmentally friendly tertiary industry. If the industrial structure is upgraded to a clean service sector, carbon emissions decrease. However, if energy-intensive industry dominates the industrial structure, pollution emissions will increase. On the other hand, in the process of population agglomeration in big cities, the exchange of knowledge generated by population agglomeration leads to innovation. Moreover, the service industry is heavily dependent on the demand generated by high population density. Therefore, population agglomeration promotes the upgradation of the industrial structure from industry-oriented to service-oriented. To verify this mechanism, we use the proportion of the added value of the secondary industry to measure the industrial structure effect. Columns (3) and (4) of Table 4 report the corresponding empirical results.

The influencing mechanism of the industrial structure has been effectively verified, namely, the agglomeration of the population in big cities increases the proportion of secondary industries. Industries with high energy consumption, high pollution, and high emissions undoubtedly increase urban carbon dioxide emissions.

Third, another influencing mechanism is the transportation effect. On the one hand, with the population agglomeration and economic growth in big cities, the personal income of residents is increasing. In addition, the proportion of transportation in the total consumption expenditure of residents is becoming higher and higher. Private car ownership is growing rapidly in Chinese cities, and the average annual growth rate of car ownership remains high. On the other hand, the increase in the number and widespread use of private cars brought about a surge in energy consumption, leading to increasing environmental problems. Moreover, the rapid increase in the permanent resident population of large cities and the rapid expansion of urban areas have increased travel and commuting distances, which has led to more and more transportation energy consumption and ultimately led to a rapid increase in transportation carbon emissions. Carbon dioxide emissions from the transportation sector are one of the main sources of carbon emissions in China. Among them, road transportation carbon emissions account for more than 80% of the total urban transportation carbon emissions. To verify this mechanism, we use the amount of private car ownership as the proxy variable to measure the traffic effect. Columns (5) and (6) of Table 4 show that the increase in urban permanent population has accelerated the expansion of private car ownership. In other words, the population agglomeration in big cities has urged more and more people to buy and use cars. The increase in car ownership has led to a rapid increase in transportation carbon emissions.

As a result, the effects of industrial structure and transportation are the main reasons for the increase in carbon emissions. In the process of rapid population agglomeration in big cities, the failure of the industrial structure to upgrade to a clean and low-carbon industry is one of the main reasons for the increase in carbon emissions. In addition, the agglomeration of the population in large cities has promoted an increase in the number of private car ownership. Then, the ownership and use of private cars have promoted the increase in transportation carbon emissions and ultimately increased the city's carbon emissions. The technological innovation effect can reduce urban carbon emissions but cannot offset the increase in carbon emissions caused by the effects of industrial structure and transportation.

Population agglomeration and carbon dioxide emissions in big cities: instrumental variable estimation

Endogeneity and its instrumental variables

In the relationship between population agglomeration and carbon emissions, the endogeneity mainly comes from the problem of missing variables. Population agglomeration may be related to many unobserved factors which may influence carbon emissions, so we use the method of instrumental variables to solve it. We use the urban land supply growth rate as an instrumental variable for the urban permanent population. Specifically, on the one hand, the urban land supply will directly affect the built-up area of the city and the capacity to accommodate the permanent population. On the other hand, the land supply in Chinese cities is determined by the higher-level administrative departments, so the growth rate of land supply is exogenous.

Instrumental variable regression results

Table 5 reports the results of instrumental variable regression based on Eq. (1) within the framework of 2SLS. The regression result in column (1) shows that the permanent population increases by 1%, and carbon emissions increase by 0.5543%. Column (2) shows that the residential density increases by 1%, and the carbon emissions increase by 0.8285%. Land supply directly change the area of built-up areas, which in turn change the residential density and urban permanent population. The coefficient of land supply growth rate is significantly negative in the first stage of regression. The F value of the first stage regression is significantly greater than 10, which means that a strong correlation exists between the instrumental variable of land supply growth rate and the endogenous variable. Columns (3) and (4) show that after the instrumental variables are put into the model, and the urban permanent population and

residential density are controlled simultaneously, the impact of instrumental variables on carbon emissions has no statistically significant correlation.

Further discussion: nonlinear estimation of population agglomeration and carbon emissions in big cities

The impact of urban population agglomeration on carbon emissions is complex, and the impact of different levels of large cities on carbon emissions may be nonlinear. Therefore, we further explore the impact of population agglomeration of different population scale on carbon emissions to provide constructive policy implications for future urban development strategies. According to the “Notice on Adjusting the Criteria for City Size Classification” issued by the State Council in 2014, cities with an urban permanent resident population of more than 1 million and less than 5 million are defined as large cities. Among them, cities with more than 3 million and less than 5 million are defined as type I large cities, and those with more than 1 million and less than 3 million are type II large cities. In addition, cities with urban permanent populations of more than 5 million and less than 10 million are defined as megacities, and those with an urban permanent resident population of more than 10 million are classified as megalopolises. Based on the “Notice,” this article divides big cities into four grades according to the size of the city's permanent resident population (1–3 million, 3–5 million, 5–10 million, and more than 10 million). The study introduces three dummy variables, D_1 , D_2 , and D_3 , that represent the different size of the urban permanent resident population:

$$D_1 = \begin{cases} 1, & \text{if } 1 \text{ million} \leq \text{permanent resident population} \leq 3 \text{ million} \\ 0, & \text{if } ELSE \end{cases}$$

$$D_2 = \begin{cases} 1, & \text{if } 3 \text{ million} \leq \text{permanent resident population} \leq 5 \text{ million} \\ 0, & \text{if } ELSE \end{cases}$$

$$D_3 = \begin{cases} 1, & \text{if } 5 \text{ million} \leq \text{permanent resident population} \leq 10 \text{ million} \\ 0, & \text{if } ELSE \end{cases}$$

We build the following model (3):

$$\ln(CO_2)_{it} = \beta_0 + \beta_1 \ln P_{it} + \beta_2 D_1 * \ln P_{it} + \beta_3 D_2 * \ln P_{it} + \beta_4 D_3 * \ln P_{it} + \beta X_{it} + \gamma_t + \eta_i + \epsilon_{it} \quad (3)$$

Among them, D_1 , D_2 , and D_3 are dummy variables, which represent the classification of big cities according to the size of the permanent population. By introducing a cross term formed by a dummy variable and a city's permanent population, the nonlinear effects of changes in

Table 6 Population agglomeration and carbon emissions in big cities: estimation results of the nonlinear relationship

Independent variable	Dependent variable $\ln(CO_2)$		
	(1)	(2)	(3)
$\ln P$	0.0484* (0.0268)	0.0482* (0.0268)	0.0489* (0.0267)
$D_1 * \ln P$	0.0134** (0.00669)	0.0136** (0.00677)	0.0135** (0.00677)
$D_2 * \ln P$	0.0121** (0.00542)	0.0123** (0.00550)	0.0124** (0.00553)
$D_3 * \ln P$	0.00557 (0.00423)	0.00557 (0.00427)	0.00559 (0.00432)
GDP per capita	0.647*** (0.214)	0.641*** (0.226)	0.639*** (0.225)
Square of GDP per capita	-0.00706 (0.0100)	-0.00684 (0.0104)	-0.00759 (0.0104)
Energy efficiency	-0.0556*** (0.0142)	-0.0552*** (0.0140)	-0.0540*** (0.0137)
Economic openness	-0.286 (0.228)	-0.287 (0.229)	-0.244 (0.226)
Proportion of secondary production		0.0000876 (0.000556)	-0.0000269 (0.000556)
Transportation			0.0203 (0.0129)
Constant term	-3.320*** (1.194)	-3.288*** (1.264)	-3.254** (1.252)
Urban-fixed effect	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes
N	2659	2657	2657
R^2	0.884	0.884	0.885

carbon emissions caused by different population scales are estimated. P is the city’s permanent population, and the city’s CO_2 emissions are the dependent variable. X refers to control variables, including GDP per capita, energy efficiency, the proportion of secondary industries, transportation, and economic openness. \ln refers to the natural logarithm, subscripts t and i refer to time and city, and ε refers to standard error. γ_t means controlling annual fixed effects, and η_i means controlling urban fixed effects. Table 6 shows the estimation results.

From column 1 of Table 6, for the megalopolises with a permanent urban population of more than 10 million, every 1% increase in the urban permanent population will increase carbon dioxide emissions by 0.0484%. In large cities with a permanent resident population of between 1 and 3 million, every 1% increase in the urban permanent resident population will increase carbon dioxide emissions by 0.0618% (0.0484 + 0.0134). In large cities with a permanent resident population of between 3 and 5 million, every 1% increase in the urban permanent population will increase

Table 7 Population agglomeration and carbon emissions in big cities: results of the nonlinear relationship

	(1)	(2)	(3)
$\ln P$	0.684*** (0.252)	0.687*** (0.252)	0.680*** (0.251)
$(\ln P)^2$	-0.0622*** (0.0235)	-0.0624*** (0.0235)	-0.0617*** (0.0235)
GDP per capita	0.551** (0.226)	0.561** (0.232)	0.561** (0.231)
Square of GDP per capita	-0.00291 (0.0107)	-0.00321 (0.0109)	-0.00401 (0.0110)
Energy efficiency	-0.0567*** (0.0141)	-0.0572*** (0.0140)	-0.0560*** (0.0137)
Economic openness	-0.328 (0.226)	-0.331 (0.227)	-0.290 (0.224)
Proportion of secondary production		-0.0000959 (0.000550)	-0.000202 (0.000549)
Transportation			0.0190 (0.0125)
Constant term	-4.308*** (1.101)	-4.372*** (1.149)	-4.332*** (1.139)
Urban-fixed effect	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes
N	2659	2657	2657
R^2	0.887	0.887	0.888

carbon dioxide emissions by 0.0605% (0.0484 + 0.0121). The coefficient of the crossterm $D_3 * \ln P$ is not significant, that is, for megacities with urban permanent residents in the range of 5–10 million, the increase in the size of the urban population has insignificant impact on the increase in carbon emissions. Column 2 adds the control variable of the proportion of the secondary industry, and the result is similar to column 1. The coefficient of $\ln P$ is 0.0482, that is, for megalopolises with a permanent urban population of more than 10 million, every 1% increase in the urban permanent population increases carbon dioxide emissions by 0.0482%. The coefficient of $D_1 * \ln P$ is 0.0134, indicating that in large cities with a permanent population of 1–3 million, every 1% increase in the urban permanent population will increase carbon dioxide emissions by 0.0618% (0.0482 + 0.0136). The coefficient of $D_2 * \ln P$ is 0.0123, which means that in a large city with a permanent population of 3–5 million, every 1% increase in the urban permanent population will increase carbon dioxide emissions by 0.0605% (0.0482 + 0.0123). The coefficient of the cross term $D_3 * \ln P$ is not significant. The control variable of transportation is added to the third column, and the number of private cars is used as the proxy variable of transportation. The result is similar to the second column. That is, the coefficients of $\ln P$, $D_1 * \ln P$, and $D_2 * \ln P$ are all significantly positive, with $D_1 * \ln P$ having the

biggest coefficient, followed by $D_2 \cdot \ln P$ and $\ln P$. The coefficient of $D_3 \cdot \ln P$ failed to pass the statistical test.

The results show that, for cities with different population sizes, the permanent resident population of the city has a positive correlation with carbon emissions. The impact of the permanent resident population of large cities on carbon dioxide shows nonlinear change, initially increases, and then decreases with the increase of the permanent resident population. For type II large cities with a permanent resident population of between 1 and 3 million, the increase in carbon emissions brought about by population growth is the largest, followed by large cities with a permanent population of between 3 and 5 million. Megacities with a permanent population of more than 5 million have the least impact on carbon emissions. Specifically, in megacities with permanent residents between 5 and 10 million, the impact of population growth on carbon emissions is not significant. Thus, to achieve the goal of carbon emission peak and carbon neutrality, China may need to develop megacities with urban permanent residents between 5 and 10 million.

To further verify the nonlinear relationship between the urban permanent resident population and carbon dioxide emissions, as shown in Eq. (4), this study replaces the cross term in Eq. (3) with the square term of urban permanent population ($\ln P_{it}^2$). Table 7 shows the regression results.

$$\ln(CO_2)_{it} = \beta_0 + \beta_1 \ln P_{it} + \beta_2 (\ln P_{it})^2 + \beta X_{it} + \gamma_t + \eta_i + \varepsilon_{it} \quad (4)$$

The results of columns (1), (2), and (3) of Table 7 show that the quadratic term of the urban permanent population is negative at the 1% significance level. The linear term of the urban permanent population is positive at the 1% significance level. This case means that an inverted U-shaped nonlinear relationship exists between urban permanent population and carbon emissions. In the initial stage of population agglomeration in big cities, population agglomeration leads to a sharp increase in carbon emissions. After the population agglomeration reaches the turning point value, carbon dioxide emissions begin to show a downward trend with the growth of urban population.

Case study

It has been proved in our manuscript that big cities with different population have different effects on carbon emissions. In order to further verify the reliability of the above conclusion, we take 4 cities, for example, as a case study.

Jingmen City was selected as a representative of type II big cities with an urban permanent resident population of 1 million to 3 million. Located in the middle of Hubei Province, Jingmen is an important city of Mid-Yangtze River Urban Agglomerations, a regional central city in Hubei.

Jingmen has a built-up area of 67.65 km², and its urban permanent resident population had reached 2.597 million in 2020. Jingmen City, as the core city in the densely populated central Hubei region, has attracted a large number of foreign population. Therefore, we study the impact of population agglomeration on the local carbon emissions in Jingmen.

Jieyang City is the representative of type I big cities with an urban permanent resident population of 3 million to 5 million. Jieyang City located in the east of Guangdong Province. It is an important city of Shantou-Chaozhou-Jieyang metropolitan area and the geographical axis center between Guangdong-Hong Kong-Macao Great Bay Area and Western Taiwan Straits Economic Zone. In terms of transportation, Jieyang has convenient land and water transportation. It is an important transportation hub connecting eastern Guangdong, southwestern Fujian, and southern Jiangxi. The built-up area of Jieyang City has reached 155.10 km² in 2020, and the urban permanent population was 5.5778 million. As an emerging type I big city, the impact of population growth on carbon emission deserves attention.

The representative of megacities with an urban permanent resident population of 5 million to 10 million is Suzhou City. Suzhou is located in the southeast of Jiangsu Province, adjacent to Shanghai. It is an important central city in the Yangtze River Delta, a high-tech industrial city, and a famous scenic tourism city. In 2020, the built-up area of Suzhou has reached 481.33 km², and the urban permanent resident population has reached 12.748 million. With rapid development in recent years and undertaking Shanghai's spillover population, the population agglomeration in Suzhou increased rapidly.

Shenzhen was selected as the representative of megalopolis with a population of more than 10 million. Shenzhen is located in the southern coastal area of Guangdong Province and adjacent to Hong Kong. It is China's Special Economic Zone, an international city, a national economic center city, and an international transportation hub. It plays an important role at home and abroad. The built-up area of Shenzhen has reached 955.68 km² in 2020, and the urban permanent resident population has achieved 17.56 million. The rapid development of Shenzhen is an epitome of China since the reform and opening-up. The case study of Shenzhen is of great significance to examine the relationship between rapid population agglomeration and carbon dioxide emissions.

The regression results in Table 8 are based on Eq. (1). We see that there is a significant positive correlation between population agglomeration and carbon dioxide emissions in Jingmen, Jieyang, and Shenzhen. With the increase of urban population, carbon dioxide emissions increase. Specifically, of the regression results of Jingmen, Jieyang, and Shenzhen, the core explanatory variable's coefficient of Shenzhen (0.416) is the smallest, followed by Jieyang (1.27), and the coefficient of Jingmen (2.54) is the largest. The regression

Table 8 Relationship between cities with different population sizes and carbon dioxide emissions

Variables	The explained variable is CO ₂			
	(1)	(2)	(3)	(4)
	Jingmen City	Jieyang City	Suzhou City	Shenzhen City
<i>lnP</i>	2.540* (1.094)	1.270*** (0.225)	0.431 (0.459)	0.416* (0.213)
GDP per capita	0.0000307 (0.0000118)	0.00000894 (0.0000202)	0.0000178 (0.00000994)	0.00000800 (0.0000151)
Square of GDP per capita	−1.63e-10 (8.80e-11)	1.45e-10 (3.63e-10)	−4.20e-11* (2.08e-11)	−4.78e-11 (5.03e-11)
Energy efficiency	−0.0000434*** (0.00000971)	−0.000224** (0.0000671)	−0.000127 (0.0000813)	0.00000488 (0.00000362)
Economic openness	−2.612 (1.729)	−2.661* (1.390)	1.691 (2.228)	−5.531 (10.87)
Proportion of secondary production	0.00981* (0.00451)	−0.0261*** (0.00449)	−0.00637 (0.0104)	−0.00281 (0.0119)
Constant term	−5.884 (4.994)	1.319 (0.777)	5.956** (2.228)	5.184** (1.921)
<i>N</i>	13	13	13	13
<i>R</i> ²	0.987	0.997	0.986	0.978

results of Suzhou is not significant. Therefore, in order to achieve the goal of carbon emission peak and carbon neutrality, China may need to develop megacities with an urban permanent resident population of 5–10 million at present. The four cases' results are consistent with the previous regression results, which proves the reliability of our conclusions again.

Conclusions and policy implications

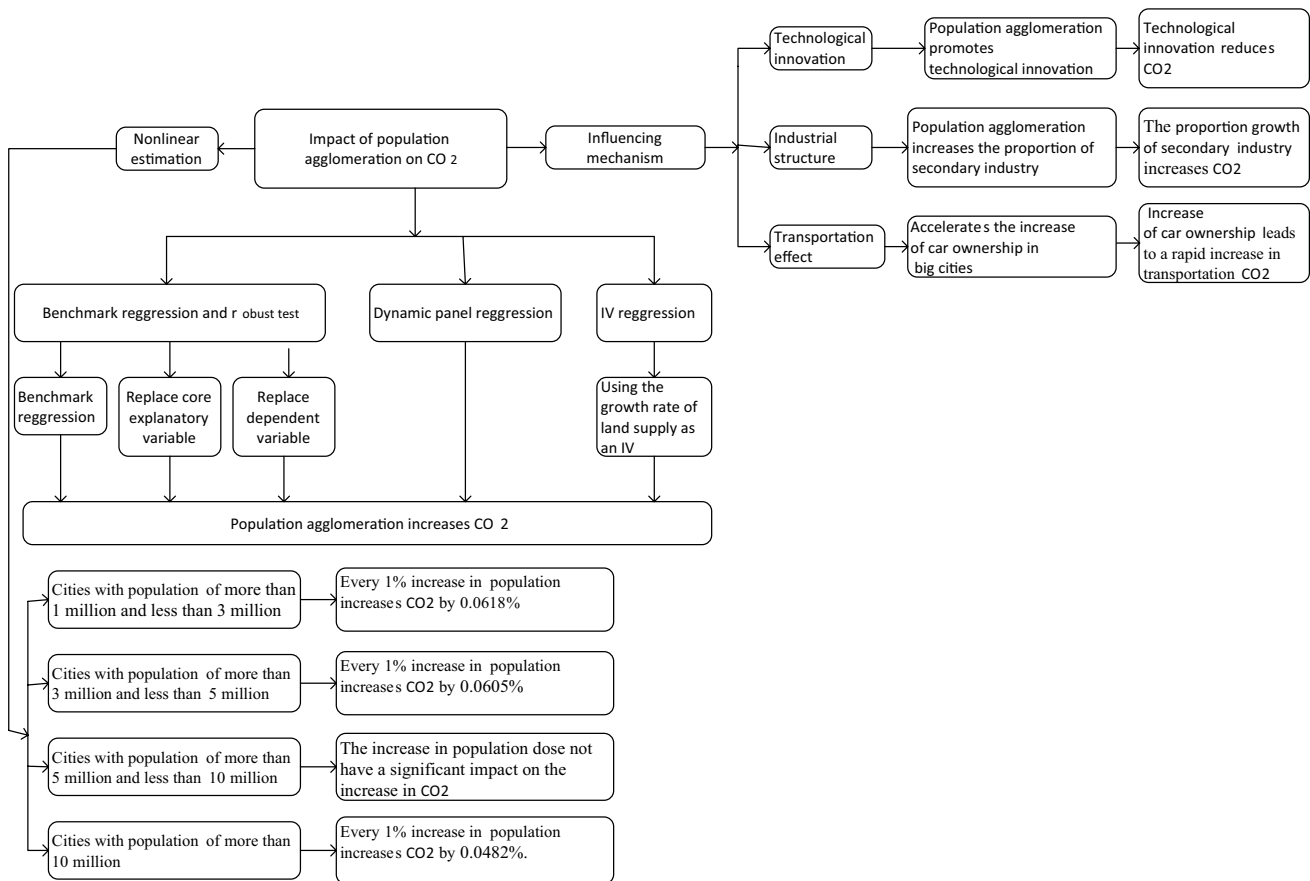
The study explored the influencing mechanism of population agglomeration in large cities on carbon emissions, including technological innovation, industrial structure, and transportation effects. Moreover, we attempt to explore the nonlinear impact of population agglomeration in large cities on carbon emissions. This article uses the large cities with more than 1 million permanent resident population in Chinese cities as the sample for the first time and the urban carbon dioxide data from the China Emission Accounts and Datasets.

This article uses the panel data of Chinese cities from 2005 to 2018 as the sample to study the impact of population agglomeration in large cities on carbon emissions. The study found that the urban permanent population is significantly positively correlated with carbon dioxide emissions. The results of the dynamic panel model regression and robustness test also confirmed that as the population agglomerated in big cities, the increase in urban permanent population significantly increased carbon dioxide emissions. The instrumental variable estimation further validates the above results. Mechanism analysis shows that the effects of

industrial structure and transportation are the main channels through which population agglomeration in large cities affects the growth of carbon emissions. That is, in the process of rapid population agglomeration in big cities, the failure of the industrial structure to achieve clean and low-carbon upgrades is one of the main factors for the increase in carbon emissions. In addition, the population agglomeration in big cities has promoted the increase in private car ownership, which has led to an increase in urban traffic carbon emissions. The effect of technological innovation can reduce urban carbon emissions but is not enough to offset the increase in carbon emissions caused by the effects of industrial structure and transportation. The empirical results also found that an inverted U-shaped nonlinear relationship exists between urban permanent resident population and carbon emissions. The impact of urban permanent resident population on carbon emissions is different under different city levels. Furthermore, with the increase of permanent resident population, the impact of urban permanent population on carbon dioxide initially increases and then decreases. For those cities with a permanent resident population of 1–3 million people, the carbon emission increase effect of population growth is the largest. As the size of the urban population increases, the effect of population growth on carbon emissions gradually becomes smaller. For megacities with a permanent resident population of 5–10 million, the impact of population growth on carbon emissions is not significant.

The main limitation of this study lies in that heterogeneity tests are not available. Heterogeneity tests such as geographic differences, urban characteristics may be included to find more variations for future researches.

Appendix Flowchart



Author contribution Yanchun Yi designed this study and participated in all phases; Dong Chen analyzed the data; Ji Qi contributed analysis tools; Ji Qi and Yanchun Yi revised the paper together. All authors read and approved the final manuscript.

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Data Availability The datasets generated and/or analyzed during the current study are available in the National Bureau of Statistics of China, <https://data.stats.gov.cn/easyquery.htm?cn=C01>.

Declarations

Ethical approval Not applicable

Consent for publication Not applicable

Consent to participate Not applicable

Competing interests The authors declare no competing interests.

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