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The impact of urbanization on carbon emissions: both from heterogeneity and mechanism test

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Abstract
It is of great significance to understand the relationship between urbanization and carbon emissions and the impact mechanism, which can help formulate climate policies and provide insights into how to achieve lower emissions with the urbanization development. Utilizing China's provincial panel dataset during period 2003–2015, this study employed the "Threshold-STIRPAT" model to investigate the impact of urbanization on carbon emissions under different urbanization thresholds, with the intermediate effect model combined. Initially, the results show that, once the urbanization development rate is less than 47.04%, each 1% increase in urbanization rate will increase the carbon emission by 0.23%, and while once the urbanization rate is greater than 47.04%, each 1% increase in urbanization rate will increase carbon emissions by 0.78%. Moreover, the intermediary transmission mechanisms, from the aspect of the improvement in resident consumption level, technological progress, industrial restructuring and energy structure adjustment, account for 1.24%, 0.78%, 0.05% and 0.02%, respectively. Ultimately, the resident consumption improvement and technological progress play the main transmission role through the empirical study of the whole sample and heterogeneous urban samples. The research results are expected to give inspiration to low carbon policies making in different urbanization stages, and to guide the direction how to optimize resident consumption and technology progress.

Keywords Urbanization · Carbon emission · Threshold-STIRPAT model · Mediating effect model

1 Introduction

In recent years, global warming problem is becoming more and more serious, which has brought many natural disasters like frequent extreme weather, threatening human survival and development (Bai et al., 2019). At the same time, the voice of building a "low-carbon

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ecological city" is becoming stronger and stronger, and more attention has been paid to the relationship between urbanization and global warming (Sharma, 2011). Especially in developing countries facing the dual dilemma of urbanization and carbon emission reduction, carbon emission reduction is imperative in order to curb the deteriorating climate environment and achieve a high-quality and sustainable urbanization development.

After more than 40 years of reform and opening up, China has experienced wealth and prosperity and the urbanization level has improved significantly. The economic boom in turn has led to an increase in carbon emissions. The contradiction between ecological environment and economic development is becoming increasingly acute.

China, as the world's largest CO_2 emitter, is facing huge pressure of international carbon emission reduction obviously. Chinese central government has developed a groundbreaking target to control greenhouse gas emission, deciding that the carbon emission intensity should be cut by 60–65% in 2030 above 2005 levels and the peak CO_2 emissions will be achieved by the latest 2030 (Fang et al., 2021). However, China's urbanization has entered a critical period of in-depth development and some scholars predict that it will reach 80% in 2050, meaning that China's urbanization rate has a high-speed growth trend for a long time in the future, and the rapid growth of high-carbon energy demand not been much change. It leads to an arduous task for the carbon emission mitigation. Therefore, taking the differences of urbanization development stages in various regions of China as the starting point, this study explored the relationship between urbanization and carbon emission and the specific mechanism of urbanization affecting carbon emission, which is a necessary prerequisite for formulating practical carbon emission reduction policies. It is extremely important to accelerate new urbanization construction in the pursuit of sustainable development at this stage. As people pay more and more attention to the interaction between urbanization and carbon emissions, there is increasing research in this field, such as the relationship between two and the impact mechanism of the two.

The existing research on the relationship between urbanization and carbon emissions has not reached a consensus on whether the process of urbanization and carbon emission reduction can reach a harmonious state. A large number of literature claim that urbanization increases energy demand and produces more carbon emissions (Chen et al., 2020; Sun et al., 2018; Wang et al., 2021; Yao et al., 2018). Scholars who hold this view believe that the extensive expansion of cities has brought large-scale population aggregation and more intensive urban economic activities, resulting in an increase in energy demand and carbon emissions in the fields of residence, transportation, entertainment and so on. Moreover, some scholars further believe that it is impractical to reduce the total amount of carbon emissions because the urbanization process is still fully promoted at this stage. However, some studies argue that there is a negative relationship between urbanization and carbon emissions (Tang et al., 2021; Xu et al., 2018; Zhang et al., 2021; Zhou et al., 2021). Among them, Zhang et al. (2021) found that urbanization reduces energy consumption and carbon emissions by improving the efficiency of people's use of public infrastructure such as public transportation. What is more, many scholars believe that the impact of urbanization on carbon emissions varies with the urbanization process and economic development stage of the research samples (Ponce de Leon Barido & Marshall, 2014; Sharma, 2011; Shi & Li, 2018; Tripathi, 2021; Wang & Su, 2019; Xie & Liu, 2019). For example, Tripathi (2021) tested samples from different countries and found that carbon emissions increased rapidly in the early and middle stages of urbanization, but in the late stage of urbanization, although the total carbon emissions still increased, the speed and intensity of carbon emissions showed a downward trend. Furthermore, Wang and Su (2019) made it clear that in the late stage of urbanization, due to the role of scale effect and technological progress, continuous urbanization will reduce the total carbon emission, and there is a U-shaped relationship between urbanization and carbon emission.

Obviously, there are completely diverse conclusions with regard to the effect of urbanization on carbon emissions. Possible reasons are as follows. First, the effect of urbanization on carbon emissions depends on the country's economic development level. The results are diverse when the sample intervals are different, that is, the research objects are in various economic development stages (Martínez-Zarzoso & Maruotti, 2011). Second, different model specifications and indicators have a great influence on regression results, leading to uncertainty of final results.

In terms of the impact mechanism of urbanization and carbon emissions, the existing research focuses on some key factors. Ghazouani (2021), for example, studied that a country's per capita GDP and the proportion of service industries are important factors affecting the relationship between urbanization and carbon emissions. Additionally, many factors can influence carbon emissions, including technological progress (Sun & Huang, 2020), resident consumption level (Wang et al., 2018), human capital accumulation (Wu & Zhang, 2021), industrial structure (Madlener & Sunak, 2010), energy consumption structure (Bai et al., 2019), energy efficiency (Perry, 2014), clean energy use (Ding & Li, 2017) and so on. To some extent, most existing studies concentrate on the influence path among the above factors. However, little attention has been paid to how the impact factors work and how much they work.

Therefore, there is a great need to explore and reveal the influence channels of urbanization on carbon emissions from the perspective of heterogeneity and mechanism tests. This research constructs a "Threshold-STIRPAT" model and carries out empirical research based on the panel data of 30 Chinese provinces from 2003 to 2015. By judging the threshold effect and threshold of urbanization, it depicts the heterogeneity pattern of urbanization's impact on carbon emissions. Furthermore, the corresponding intermediary variables are selected to clarify the specific size and comparative relationship of each intermediary factor, which help achieve a more effective and targeted analysis of urbanization and carbon emissions.

2 Theoretical mechanism

Serious carbon emission in China's urbanization process mainly comes from economic and policy incentives (Yao et al., 2021). The research mainly analyzes the following four economic factors: the improvement in resident consumption level, the progress of technology, the adjustment of industrial structure, and the adjustment of energy structure.

2.1 The promotion mechanism of resident consumption level

Urban resident consumption structure and level have been changing with the deepening of urbanization (Hao, 2014), which directly affects the total energy consumption and then carbon emissions. On the one hand, urban residents will directly increase their consumption of coal, oil, natural gas and other essential energy for daily life. On the other hand, urban resident consumption demand will be biased toward housing, private cars, tourism and other aspects, which will also lead to the growth of energy consumption and carbon emissions (Li et al., 2021). Chinese low carbon report shows that the gap between rural and urban resident domestic energy consumption has been widening during 1996–2010 (Wu et al., 2016). In the 15 years, the increase of residential energy generated by urban residents transformed from farmers has produced huge carbon emissions, reaching 447 million tons.

With the continuous improvement in urban consumption level, on the one hand, the environmental pollution caused by excessive consumption demand will force urban managers to actively seek clean energy to replace traditional fossil energy and promote the improvement in energy efficiency through technological innovation and environmental regulation policies, so as to curb the continuous growth of carbon emissions. On the other hand, compared with rural residents, urban residents tend to consume green products and low-carbon products, and their lifestyles prefer to be low-carbon and environmental-friendly. As a result, cities and towns will have greater carbon emission reduction potential. To sum up, the effect of urbanization on carbon emissions through the improvement in consumption level is actually two-way.

2.2 The mechanism of technological progress

The process of urbanization and industrialization is always synchronous (Sun et al., 2022). The production technology is also improving rapidly in the process of rapid development of industrialization. As known, technological progress is a double-edged sword. Similarly, technological progress has two effects on carbon emissions: for one thing, technological progress will accelerate the upgrading of fossil energy and the use of clean energy, which is directly conducive to the improvement in energy efficiency and energy structure. What is more, it can promote the transformation of economic development to cleaner and more low-carbon and so as to reduce carbon emissions in the process of economic growth; For another, due to the improvement in production efficiency brought by technological progress, the material capital and human capital required for production will decrease and enterprises will reduce product prices as a result of the reduction of costs, which may stimulate consumer demand. The expansion of consumer demand will further urge manufacturers to expand production, which will eventually lead to an increase in carbon emissions. Therefore, the effect of urbanization on carbon emissions through technological progress is also two-way.

2.3 The mechanism of industrial structure adjustment

The development of urbanization is accompanied by the adjustment of industrial structure from the primary industry to the secondary and tertiary industries (Zheng et al., 2021). On the one hand, with the acceleration of the urbanization process, more and more rural labor forces will gather in cities, from agricultural production to industrial or service activities. Compared with low-carbon agriculture, the manufacturing industry inevitably will consume a lot of fossil energy in the production process, which will result in a rapid increase in total carbon emissions (Huo et al., 2020). On the other hand, similar to the reverse inhibitory effect in the mechanism of resident consumption level, with the progress of urbanization, the increasingly serious environmental problems will also force the government to optimize the industrial structure of the city, take corresponding measures to control the proportion of manufacturing industries with serious pollution, and encourage the development of high-tech industries and other less-polluting tertiary industries, which will reduce the carbon emission in the production process (Liu & Liu, 2019).

2.4 Energy structure adjustment mechanism

The energy consumption structure of urban and rural residents is naturally different. Rural product structure is usually self-sufficient and the energy consumption is relatively small. However, urban households not only consume more energy, but also mainly from fossils, which will lead to more carbon emissions. What is more, the widening income gap between urban and rural residents should further widen the difference in energy structure (Li, 2021). The relatively high income of urban residents will stimulate consumer demand, and the demand for industrial manufactured goods will increase accordingly. As a result, with the prosperity and development of the manufacturing industry, urban energy consumption structure will be dominated by fossil energy, which usually has the characteristics of high carbon emission. On the other hand, the urbanization level with sustained and rapid growth will also promote the transformation of production technology into a green and environmentally friendly type. Moreover, it can guide enterprises to use more green and clean energy in production to meet consumer demand, which will be achieved by changing consumer preferences. Then the growth of carbon emissions will be inhibited efficiently.

3 Model construction and index data selection

3.1 Threshold-STIRPAT model

It has been proved that there is a nonlinear relationship between urbanization and carbon emissions (Adebayo et al., 2021; Hashmi et al., 2021). As mentioned in Sect. 1, different urbanization levels may have different impacts on carbon emissions. Hence, we use the threshold regression model (Hansen, 1999) which has been widely employed to analyze the influencing factors of carbon emissions to identify potential inflection point(s) at different urbanization stages under the condition of considering the influences of the control variables (i.e., the factors that may have important effects on the dependent variable except for the key independent variable). Combined with the practical problems to be studied in this research, the standard form of the STIRPAT model is extended to construct the following single Threshold-STIRPAT model:

$$\begin{aligned}\ln Pc_{it} =& \alpha_1 \ln Ur_{it}(Ur_{it} \le \eta_1) + \alpha_2 \ln Ur_{it}(Ur_{it} > \eta_1) + \beta \ln Con_{it} + \gamma \ln Ee_{it} \\ &+ \delta Indp_{it} + \lambda Fdip_{it} + \varphi Enstrp_{it} + v_{it}\end{aligned} \tag{1}$$

where i and t represent provinces and years, respectively, Pc is per capita carbon emissions, Ur is urbanization level, Con is per capita consumption level of urban residents, Ee is energy efficiency, $Indp$ is the proportion of industrial added value in GDP, $Fdip$ is the proportion of actually utilized foreign capital in GDP, $Enstrp$ is the proportion of environmental protection investment in GDP, η is the threshold value of urbanization level to be estimated and v_{it} is the error term of the model. The model form of double threshold can be expressed as follows:

$$\begin{aligned}\ln Pc_{it} =& \alpha_1 \ln Ur_{it}(Ur_{it} \le \eta_1) + \alpha_2 \ln Ur_{it}(\eta_1 < Ur_{it} < \eta_2) + \alpha_3 \ln Ur_{it}(Ur_{it} \ge \eta_2) + \beta \ln Con_{it} \\ &+ \gamma \ln Ee_{it} + \delta Indp_{it} + \lambda Fdip_{it} + \varphi Enstrp_{it} + v_{it}\end{aligned} \tag{2}$$

3.2 Mediating effect model

Pu et al. (2020) summarized the causal relationship between urbanization and carbon emissions, including direct causal effect, mediated causal effect, and moderated causal effect. This study employs four mediating variables to investigate the relationship between urbanization and carbon emissions based on the above idea. These four mediating variables are *Con*、*Ee*、*Indp* and *Enstrp* which have been introduced in Sect. 3.1.

The mediating variable is conducive to understanding the effect path of the independent variable on the dependent variable (Hayes, 2009). Furthermore, it is necessary to incorporate more than one mediating variable, to more clearly explain the effect of the independent variable on the dependent variable under a complex condition. It is an appropriate approach to analyze the multiple mediating effect model through the structural equation model, which can simultaneously handle explicit variables and latent variables, as well as the relationships among multiple independent variables, multiple dependent variables, and multiple mediating variables (Cheng et al., 2021). Moreover, the multiple mediating effect model can be classified into the single-step multiple mediating effect model and the multiple-step multiple mediating effect model according to whether there are any interactions between the multiple mediating variables (Wang et al., 2019). In this study, we assume that there is no interaction between *Con*、*Ee*、*Indp* and *Enstrp*. Therefore, the single-step multiple mediating effect model is employed to test the mediating effects of related factors on the relationship between urbanization and carbon emissions.

Scholars generally use the sequential test method proposed by Baron and Kenny to test the mediating effect (Yao et al., 2021). This research improves the domestic scholars' research on this method by combining sequential test and bootstrap method. We will test the four coefficients c, a, b, c' in (3)–(6) in turn, if they are all significant, it indicates that there is a mediating effect. If a or b is not significant, bootstrap test can be used. If the test result is significant and the confidence interval does not contain 0, then there is a mediating effect.

$$Y = cX + \varepsilon_1 \tag{3}$$

$$M_{\mathrm{i}} = \mathrm{a}_i\mathrm{X} + \varepsilon_{2i} \tag{4}$$

$$Y = c_{\mathrm{i}}'X + b_iM_i + \varepsilon_{3i} \tag{5}$$

$$Y = \mathrm{c}'X + b_1M_1 + b_2M_2 + b_3M_3 + b_4M_4 + \varepsilon_4 \tag{6}$$

In the above formulas, X and Y, respectively, represent *Ur* and *Pc*, M_1、M_2、M_3、M_4 represent *Con*、*Ee*、*Indp* and *Enstrp,* respectively, and the coefficients a_1, a_2, a_3, a_4 represent the impact of X on each intermediary variable, while the coefficients b_1、b_2、b_3、b_4 represent the impact on per capita carbon emissions of each intermediary variable when the urbanization rate is controlled. The single mediating effect is a_ib_i, and the total mediating effect is $\sum_{\mathrm{i}=1}^{4} a_ib_i(\mathrm{i} = 1, 2, 3, 4)$. The sum of the total mediating effect and the direct effect is the total effect.

3.3 Data and sources

The data used in this research is the panel data of 30 provinces in China from 2003 to 2015. Due to the lack of data, Hong Kong, Macao, Taiwan and Tibet are not included. The data of coal, oil and natural gas used to calculate carbon emissions and total energy consumption are from Chinese energy statistical yearbook (2004–2016), the data of urbanization rate, the consumption level of urban residents, industrial added value and environmental protection investment are from Chinese Statistical Yearbook (2004–2016), and the data of actually utilized foreign investment are from the statistical yearbooks of various provinces. The missing data in the Yearbook can be supplemented by the compilation of 60 years of new China and the government statistical bulletin. In order to avoid the impact of price changes, the price is adjusted according to the constant price in 2003. At the same time, *Indp, Enstrp, Fdip* and *Envirop* are not in %, but take values between (0, 1) to avoid a great difference in model coefficients. The descriptions and descriptive statistics of variables are shown in the following Tables 1 and 2.

4 Analysis of empirical results

4.1 Threshold effect of urbanization on carbon emission

According to the Threshold-STIRPAT model, stata13 software was used for data processing. The fixed-effect model was selected for the reason that the Hausman test rejected the random effect model. Tables 3 and 4 show the results of the threshold test and threshold regression. It can be seen from Table 3 that it is appropriate to choose the single threshold model, and the corresponding threshold value is 47.04%.

According to Table 4, when the urbanization rate is less than 47.04%, urbanization promotes carbon emissions; when the urbanization rate is more than 47.04%, urbanization enhances the promotion of carbon emissions. In summary, urbanization promoted carbon emissions in the whole sample period.

The promotion effect of urbanization rate on carbon emissions is closely related to the four mediators. The impact of these variables on carbon emissions is as follows: (1) Consumption level: *Con* has a positive and significant effect on *Pc*, *Pc* will increase by 1.02% for every 1% increase in consumption level of urban residents. That is to say, the higher the per capita consumption level of urban residents, the larger the per capita carbon emissions scale. The improving consumption level of urban residents means an increase in the consumption of durable consumer goods such as televisions and refrigerators, which are also high carbon emission products, leading to the expansion of energy consumption and the growth of carbon emissions. (2) Energy efficiency: the improvement in energy efficiency can inhibit the growth of carbon emissions. Every 1% increase in energy efficiency will reduce carbon emissions by 0.82%. The positive effect of technological progress is reflected in the model. The improvement in energy utilization and the increase of clean energy use can reduce carbon emissions accordingly. (3) Industrial structure: for every 1% increase in the proportion of industrial output value, carbon emissions will increase by 0.87%. With regional advantages, urban areas constantly attract labor and industrial agglomeration, and the rapid development of the secondary industry is bound to be accompanied by the high consumption of energy and

Table 1 Descriptions of variables

	Variable symbol	Variable name	Processing method
Dependent variable	Pc	Per capita carbon emissions	Total carbon emissions (IPCC) / total population
Independent variable	Ur	Urbanization rate	Urban population / total population
Control variable	Con	Consumption level	Per capita consumption level of urban residents
	Ee	Energy efficiency	GDP / total carbon emissions
	Indp	Proportion of industrial added value	Industrial added value / GDP
	Enstrp	Energy-resource structure	Coal consumption / total energy consumption
	Fdip	Proportion of foreign investment	Actual utilized foreign capital / GDP
	Envirop	Proportion of environmental investment	Environmental governance investment / GDP

Table 2 Descriptive statistics of variables

Variable	Unit	Mean value	Standard deviation	Minimum	Maximum
Pc	T/person	7.87	5.34	1.36	30.37
Ur	%	49.01	15.71	15.58	89.6
Con	Yuan	1.5e+04	7619.35	493	4.9e+04
Ee	104/T	1.02	0.59	0.14	3.86
Indp	%	0.40	0.08	0.05	0.56
Enstrp	%	0.61	0.16	0.14	0.91
Fdip	%	0.02	0.02	0.00	0.11
Envirop	%	0.01	0.008	0.002	0.09

Table 3 Threshold effect test

	Ur threshold	F value	P
Single threshold	47.04	19.717***	0.007
Double threshold	47.69	6.363	0.12
Triple threshold	39.31	6.671*	0.07

*, **, ***, respectively, represent passing the significance test of 10%, 5%, 1%

Data source: Based on Stata software

Table 4 Results of Threshold-STIRPAT model with fixed effects

Variable name	Coefficient estimation	Standard error	T value
Lnur (Ur ≤ 47.04%)	0.227***	0.0617	3.68
Lnur (Ur ≥ 47.04%)	0.783***	0.274	2.86
Lncon	1.015***	0.105	9.67
Lnee	-0.824***	0.134	-6.15
Indp	0.878***	0.244	3.60
Enstrp	0.672*	0.348	1.93
Fdip	-0.577	1.032	-0.56
Envirop	0.507	0.844	0.60

Same as Table 3

the rapid increase of carbon emissions. (4) Energy structure: for every 1% increase in the proportion of coal consumption in the total energy consumption, per capita carbon emission will increase by 0.67%. As can be seen from Fig. 1, although China's energy structure has been improving, the total consumption of coal is still rising. It reflects that the change of energy structure is still promoting carbon emissions. The relative abundance of coal resources affects China's energy consumption pattern. At present, we should accelerate the improvement in energy efficiency and increase the use of clean energy to curb the increase of carbon emissions caused by energy disadvantage effectively. (5) Foreign direct investment: the proportion of actually utilized foreign investment has a certain inhibitory effect on China's carbon emissions, but it is not significant. Foreign investment is a double-edged sword. On the one hand, it brings the spillover of technical management experience. On the other hand, it brings resource consumption

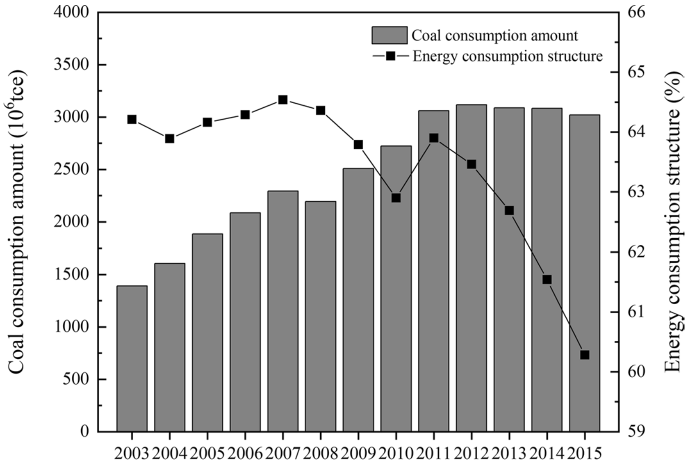

Fig. 1 Energy consumption structure and coal consumption trend

and environmental deterioration. In the future, foreign investment should be strictly screened and only high-tech and green-friendly foreign investment can be encouraged to enter the market. (6) Environmental investment: the effect of this item on carbon emissions is positive but not significant, indicating that China's increase in environmental investment leads to an increase in per capita carbon emissions. The possible explanation is that the focus of China's environmental governance at the present stage is to control the emission of traditional pollutants, and there is not enough attention paid to the greenhouse gas emission represented by CO_2. Therefore, the effect of environmental investment on inhibiting carbon emissions is very little.

4.2 The test of intermediary mechanism

A combination of sequential test and bootstrap test was used to test the mediating mechanism. According to the steps of (3) to (6) above, this research tested the mediating effects of urbanization on resident consumption level, technological progress, industrial structure and energy structure in turn.

Table 5 Test results of mediating effect of resident consumption level

	Lnpc	Lncon	Lnpc
Lnur	0.965***	1.349***	0.544***
	(0.0861)	(0.0954)	(0.135)
Lncon			0.312***
			(0.0895)
Control variable	Yes	Yes	Yes

Same as Table 3

Table 6 Test results of mediating effect of technological progress

	Lnpc	Lnee	Lnpc
Lnur	0.965***	0.948***	1.030***
	(0.0861)	(0.0931)	(0.146)
Lnee			− 0.0683
			(0.121)
Control variable	Yes	Yes	Yes

Same as Table 3

Table 7 Test results of intermediary effect of industrial structure

	Lnpc	Indp	Lnpc
Lnur	0.965***	0.0603***	0.913***
	(0.0861)	(0.0182)	(0.0847)
Indp			0.870*
			(0.489)
Control variable	Yes	Yes	Yes

Same as Table 3

4.2.1 The empirical results of resident consumption level

From the test results in Table 5, urbanization has a significant role in promoting carbon emissions, the *Lnur* coefficient is 0.965, the correlation coefficient between the consumption level of urban residents and urbanization is 1.349, and all coefficients pass the 1% significance test. Urbanization still shows good significance when the consumption level of urban residents is added, indicating that the intermediary effect of the consumption level of urban residents is significant. Therefore, urbanization promotes the increase of carbon emissions by improving the consumption level of urban residents and the mechanism proposed above is verified.

4.2.2 Empirical results of technological progress

From the test results in Table 6, urbanization has a significant promoting effect on energy efficiency, with a correlation coefficient of 0.948, which is significant at the significance level of 1%. After adding energy efficiency, the coefficient of urbanization on carbon emissions is still significant and becomes larger. The coefficient of energy efficiency on carbon emissions is negative, which is consistent but not significant and a bootstrap test is needed as a result. Stata test shows that the test P-value of indirect effect is 0, and the confidence interval is [− 0.7991, − 0.5206], excluding 0, which passes the test. Therefore, it can be concluded that energy efficiency plays a mediating role between urbanization and carbon emissions, and the mediating effect is significant. In other words, urbanization suppresses carbon emissions through technological progress and the above mechanism is verified.

4.2.3 The empirical results of industrial structure

As can be seen from Table 7, the correlation coefficient between urbanization and the proportion of industrial added value is 0.0603, which passes the significance test with the significance level of 1%. After adding the proportion of industrial added value, the correlation coefficient between urbanization and carbon emissions is 0.913, and passes the 1% significance test, which shows that the industrial structure has a mediating effect between urbanization and carbon emissions. Therefore, urbanization promotes carbon emissions by increasing the proportion of industrial added value and the third mechanism above is verified.

4.2.4 Empirical results of energy structure

It can be seen from Table 8 that the situation is similar to the second mechanism. Urbanization has an inhibitory effect on energy structure. The coefficient is -0.0397 and passes the significance test of 10%. The improvement in urbanization level will not only lead to the increase of fossil energy consumption, but also promote the unitization of clean energy. The result reflects the role of the latter. After adding the energy structure, the effect of urbanization on carbon emissions is still significantly positive and passes the 1% significance test, but the effect of energy structure is not significant. The promotion of carbon emissions is reflected in the fact that despite the decline in the proportion of coal consumption, the total coal consumption is still rising (Fig. 1). Therefore, the bootstrap test is needed. The test result shows that P-value is 0 and the confidence interval is [−0.3393, −0.145]. It indicates that urbanization increases carbon emissions by affecting the energy structure and the last mechanism is verified.

Same as Table 3

4.2.5 The proportion of each mediating effect

As shown in Table 9, the mediating role of each intermediary variable in the effect of urbanization on per capita carbon emissions is obtained: First, the coefficient of *Con* (a_1b_1) is 1.3692, which indicates that under other conditions unchanged, every 1% increase in urbanization rate will increase per capita carbon emissions by 1.3692% through the improvement in consumption level. The explanations for *Ee, Indp* and *Enstrp* are similar to it. Second, among the four mediating variables, the improvement in resident consumption level and technology progress play a major role. Third, the direct effect of urbanization on carbon emissions (c') is 0.351, the total mediating effect (ab) is 0.6143, and the total effect

Table 8 Test results of mediating effect of energy structure

	Lnpc	Enstrp	Lnpc
Lnur	0.965***	-0.0397*	1.006***
	(0.0861)	(0.022)	(0.0963)
Enstrp			1.041
			(0.677)
Control variable	Yes	Yes	Yes

Table 9 Test results of multiple mediating effects of urbanization on carbon emissions

Influence	Coefficient	Coefficient value
Direct effect		
Ur → Con	(a_1)	1.349***
Ur → Ee	(a_2)	0.948***
Ur → Indp	(a_3)	0.0603***
Ur → Enstrp	(a_4)	− 0.0397*
Con → Pc	(b_1)	1.015***
Ee → Pc	(b_2)	− 0.824***
Indp → Pc	(b_3)	0.878***
Enstrp → Pc	(b_4)	0.672*
Ur → Pc	(c’)	0.351***
Mediating effect		
Ur → Pc	(ab)	0.6143
Total effect		
Ur → Pc	(c)	0.965***

Same as Table 3

(c) is 0.965. It shows that 63.66% of the total effect is mediated by mediating variables, and the total mediating effect is 1.75 times of the direct effect.

To sum up, the results of Tables 4, 5, 6, 7, 8, and 9 show that the resident consumption level, technological progress, industrial structure, and energy structure can conduct the impact of urbanization on carbon emissions. In addition, the proportion of total mediating effect in the total effect is higher than that of direct effect in the total effect, in other words, most of the promoting effect of urbanization on per capita carbon emissions is realized through mediating variables. Of course, we cannot rule out the existence of other intermediaries.

5 Conclusion and discussion

5.1 Main achievements

In order to clarify the relationship between urbanization and carbon emissions and the specific role of the mediating transmission path, this research starts from the coupling perspective of heterogeneous urbanization and mediating mechanism, and conducts empirical research based on the STIRPAT-Threshold model and multiple intermediary effect model. The Threshold model is used to study the causal relationship between urbanization and carbon emissions, and the mediating effect model is adopted to identify the influence channel of urbanization on carbon emissions. We find that in different stages of urbanization development with 47.04% as the dividing point, urbanization promotes carbon emissions.

In addition, this research explores the impact of heterogeneous urbanization on carbon emissions through four mediating variables: urban resident consumption level, technological progress, industrial structure and energy structure. The results show that urbanization can mitigate per capita carbon emissions through improving the energy structure and technology level, while the improvement in residential consumption level and the adjustment of industrial structure can lead to the rise of per capita carbon emissions. In particular, the promotion effect of resident consumption level and industrial structure is greater than that of technological progress and energy structure improvement. Although the research results cannot lead us to the conclusion that China's industrial structure adjustment was invalid or in the wrong direction during the sample period, it enlightens us that a harmonious relationship between urbanization process and carbon emission abatement can come true if policy-makers attempt to enhance the positive mediation roles of such factors when formulating relevant policies.

5.2 Policy implications and limitations

China is experiencing rapid urbanization. It is challenging to realize the coordinated development of urbanization and carbon emission reduction. An integrated effort should be made on the basis of some policy implications.

Firstly, the Chinese government needs to implement some market-driven policies to facilitate the positive role of urbanization in energy saving and emission reduction. This is because urbanization is a necessary experience of China's economic development, yet, the abatement effect of urbanization on carbon emissions may be overshadowed by the disadvantages of the rapid expansion of urbanization. Fortunately, we are pleased to see that China is stepping toward such a goal. For one thing, China officially levied an environmental tax in 2018. Such a policy will effectively correct the distortion in fossil energy prices, enhance green technological progress, promote renewable energy use, and improve industrial structure. Hence, the introduction of an environmental tax is expected to reduce the negative impact of urbanization on carbon emission reduction, to facilitate the coordinated development of urbanization and environment, as well as the "win–win" of economic growth and carbon emission reduction. For another, China's national carbon emission trading market was officially launched on July 16, 2021. The government has been actively promoting the overall operation of the carbon trading market and providing it with financial, information and technical support. The carbon trading market is expected to mitigate China's pressure of carbon emission reduction caused by rapid urbanization and industrialization.

Secondly, the Chinese government needs to treat the adjustment of industrial structure with deliberation. This is because the upgrading of industrial structure is a sword with two blades in lowering carbon emissions. The development of manufacturing industry can lead to an increase in carbon emissions, although the reverse inhibitory effect will promote government control of highly polluting manufacturing industries and have a negative impact on carbon emissions. Therefore, the upgrading of industrial structure does not necessarily alleviate total carbon emissions. Policy-makers should focus on the development of low-carbon industries, rather than merely emphasize the manufacturing industry that promotes economic growth. In addition, regarding international industrial transfer, it is important for developing countries to avoid introducing advanced industries from developed countries in the name of climate change mitigation, but actually for promoting economic growth that may cause the increase in carbon emissions.

This study reveals the nonlinear relationship between urbanization and carbon emission at China's provincial level, which is conducive to promoting the related research on the environmental effects of urbanization. However, our study is limited by data unavailability at micro-level. Future research is suggested to investigate a wide range of issues by using more abundant data with more comprehensive independent variables, longer time span and more mediating variables, so as to provide a more reasonable explanation for the relationship between urbanization and carbon emissions.

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