Pol. J. Environ. Stud. Vol. 32, No. 3 (2023), 2393-2403
DOI: *10.15244/pjoes/160193* ONLINE PUBLICATION DATE: 2023-02-27

Original Research

The Impact of Urbanization on Carbon Emissions from Perspective of Residential Consumption

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Received: 18 November 2022
Accepted: 2 February 2023

Abstract

Rapid urbanization has significant effects on China's CO_2 emissions and contributes to climate change. It is of great theoretical and practical significance to explore the influencing factors of carbon emissions. Both the demographic composition and residential consumption of urban-rural residents were included in the expanding vector form of Kaya identity. This study employed the Logarithmic Mean Divisia Index method (LMDI) to investigate the impact of urbanization on CO_2 emissions from the perspective of residential consumption in China during 1980-2020. Six effects were included population size, urbanization, residential consumption, consumption restraint, energy intensity and emission coefficient. The results showed that residential consumption contributed far more to carbon emissions than the other five effects. The impact of urbanization on carbon emission had been greater than that of population size since the middle 1990s. The decline of residential consumption rate imposed stimulation rather than restraint on carbon emissions due to the synchronous growth of shares of higher carbon investment and export in the economy. The continuous decline of energy intensity has an obvious effect on carbon emission reduction. The research results are expected to give inspiration to guide the direction how to optimize resident consumption and to achieve green and low-carbon urbanization development.

Keywords: urbanization, residential consumption, carbon emission, factor decomposition

Introduction

The sharp global climate change caused by the increase of carbon emissions has become the focus of attention from all over the world and every country in the world is trying to find a solution. China has been the world's top energy consumer and CO_2 emitter since 2007. The total of CO_2 emission is 9.899 billion tons in 2020, accounting for 30.7% of global carbon emissions. In order to respond to global climate change actively, China has taken initiative action to strengthen carbon emission reduction. During the 75th UN General Assembly in 2020, the Chinese government promises to peak carbon dioxide emissions by 2030 and strives to achieve the goal of carbon neutrality by 2060, and China's dual-carbon goal of carbon peak and carbon neutralization has been integrated into the overall layout of ecological civilization construction since 2021, which further increased the pressure on carbon emission reduction [1]. With the annual growth of carbon emissions and the continuous upgrading of carbon emission reduction targets, academic circles

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have launched extensive discussions on China's carbon emissions.

Urbanization is considered to be a process during which most of the working population changes from farmers to a non-rural population, increasing the urban population. Urbanization is becoming the most important human social change globally, especially in developing countries [2]. China's urbanization has been a notable global event. China has witnessed a rapid improvement in its urbanization level recently [3]. The rapid development of urbanization has injected new vitality into China's politics, economy, and culture, but with the acceleration of urbanization, environmental problems have also been highlighted. There is burgeoning literature dealing with the associations between urbanization and carbon emissions. Yet the extant literature in related fields has diverged, and no unanimous conclusions have been reached. Some researchers recognize the critical role of urbanization in increasing carbon emissions [4]. 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 [5]. 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 [6]. Some vast strand of literature has documented there is a negative relationship between urbanization and carbon emissions [7]. For instance, Balsalobre-Lorente D. et al. suggested that urbanization enhances environmental quality by reducing carbon emissions [8]. Zhang et al. found that urbanization reduces energy consumption and carbon emissions by improving the efficiency of people's use of public infrastructure such as public transportation [9].

Moreover, there is still little literature focusing on the nonlinear impacts of urbanization on carbon emissions [10]. Tripathi 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 [11]. Wang and Su 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 [12]. There is an inverted U-shaped nexus between urbanization and carbon emissions, and for most OECD countries, the enhancement of urbanization is positive to increase carbon emissions [13]. In terms of the impact mechanism of urbanization and carbon emissions, the existing research focuses on some key factors, including technological progress [14], resident consumption level [15], energy consumption structure [16]. A country's per capita GDP and the proportion of service industries are important factors affecting the relationship between urbanization and carbon emissions [17]. Urban resident consumption structure and level have been changing with the deepening of urbanization [18], 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. Chinese low carbon report shows that the gap between rural and urban resident domestic energy consumption has been widening during 1996-2010 [19]. 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 [20]. To sum up, the research on the relationship between urbanization and carbon emission focuses on the test and analysis of correlation and causality. Despite the scientific consensus that humans have dramatically altered the global environment, we have limited knowledge of the specific forces driving those impacts [21]. One key limitation to a precise understanding of anthropogenic impacts is the absence of a set of refined analytic tools. The IPAT equation (IPAT Equation: $I = P \times A \times T$) maintains that impacts on ecosystems (I) are the product of the population size (P), affluence (A), and technology (T) of the human population in question. Ehrlich and Holdren was the first time using IPAT model to character the complexity of the factors affecting of human beings on the environment, considered that the impact of humans on the environment depends on the population size, resources using scale, energy efficiency and environmental safety in the process of production and consumption [22]. York, Dieta and Rosa put forward IPAT model of random form Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT), in order to test the population, economic and technological factors on carbon emissions coefficient of elasticity [23]. Kaya proposed the Kaya identities, the factorization method to establish relationship of the greenhouse gas emissions and the population size, the level of economic development and energy efficiency [24]. The Structural Decomposition Analysis (SDA) method [25] is mostly adopted for the quantitative research on the impact of population urbanization on carbon emissions from the perspective of residential consumption based on input-output table, and its investigation cycle is limited by the availability of data. Based on the time series data, the factor decomposition method is used to investigate the impact of population urbanization on carbon emissions, which effectively overcomes the limitations of data availability and investigation cycle in the decomposition analysis based on input-output table in the existing research. By expanding the vector form of Kaya identity, the variables such as urban-rural population structure and residential consumption are included in the scope of investigation. Logarithmic Mean Divisia Index (LMDI) method [26] is used to decompose the change of carbon emission into six effects, such as population size, urbanization, residential consumption, consumption restraint, and measure the contribution value and contribution rate of every factor. According to the decomposition results, it is analyzed the change characteristics and mechanism of the impact of population urbanization on carbon emissions, and explains its policy meaning.

Materials and Methods

Materials

The carbon emission of China's energy consumption is estimated from 1980 to 2020. The data are from China's energy balance table in China's energy statistical yearbook. The energy balance table had only physical quantity but no standard quantity in some years of the 1980s. The standard quantity is converted according to the reference coefficients of various energy sources for standard coal attached to China Energy Statistical Yearbook 2011. The energy data used as raw materials and materials are not given in a few years, the linear interpolation is used to supplement according to the change trend of such data in other years [27]. The carbon emission coefficients of various fossil fuels adopt the data adopted by the Energy Research Institute of the National Development and Reform Commission. According to the reference method recommended by the Intergovernmental Panel on Climate Change (IPCC), the corresponding carbon emissions are calculated from the consumption of various fossil energy over the years and the carbon emission coefficient of various energy sources. The emission factors over the years can be obtained from the calculated ratio of carbon emission and energy consumption in the current year (coal equivalent calculation); the energy intensity over the years can be obtained from the ratio of energy consumption in the current year to GDP of fixed base period.

The relevant data of population and economy are from China Statistical Yearbook over the years from 1981 to 2021. The index of population urbanization rate is characterized by the proportion of urban permanent residents in the total population, and the consumption data of urban and rural residents also correspond to the statistical caliber of permanent residents. The price is converted according to the unified economic data in 2000.

Methods

The classical Kaya identity establishes the quantitative relationship among population, energy, economy and carbon emissions. The expanded Kaya identity is as follows:

$$C = \frac{C}{PE} \times \frac{PE}{GDP} \times \frac{GDP}{P} \times P \tag{1}$$

where *C*, *PE*, *GDP*, and *P* denote carbon emissions, energy consumption, gross domestic product, and population respectively. Under the framework of expanded Kaya identity, the impact of urbanization on carbon emissions is investigated from the perspective of residential consumption. The demographic composition and residential consumption of urban-rural residents were incorporated into one model of expanded Kaya identity.

If *E* is the total consumption of residents, then Equation (1) can be extended to (2):

$$C = \frac{C}{PE} \times \frac{PE}{GDP} \times \frac{GDP}{E} \times \frac{E}{P} \times P \tag{2}$$

Taking the urban-rural population structure and the consumption variables of urban-rural residents into the scope of investigation, the total consumption of urban-rural residents is represented by E_u, and E_r respectively, and the number of urban-rural population is represented by P_u, and P_r respectively, then the E of total residents consumption can be expressed as:

$$E = \begin{pmatrix} \frac{E_u}{P_u} \\ \frac{E_r}{P_r} \end{pmatrix} \times \begin{pmatrix} \frac{P_u}{P} & \frac{P_r}{P} \end{pmatrix} \times P \tag{3}$$

By substituting Equation (3) into Equation (2), the extended form of Kaya identity including population urban-rural structure and resident consumption vector can be obtained:

$$C = \frac{C}{PE} \times \frac{PE}{GDP} \times \frac{GDP}{E} \times \begin{pmatrix} \frac{E_u}{P_u} \\ \frac{E_r}{P_r} \end{pmatrix} \times \begin{pmatrix} \frac{P_u}{P} & \frac{P_r}{P} \end{pmatrix} \times P \tag{4}$$

Let $Cf = \frac{C}{PE}$ represent the carbon emission per unit of energy consumption, that is, the carbon emission factor, $Ei = \frac{PE}{GDP}$ denote energy intensity, which is energy consumption per unit of GDP, $Rc = \frac{GDP}{E}$ denote consumption-suppressing factor, which is the ratio of GDP to residential consumption. It is the reciprocal of residential consumption rate, which indicates the degree of restraint of residential consumption by the economy, $e_u = \frac{E_u}{P_u}$ and $e_r = \frac{E_r}{P_r}$ denote per capita consumption in urban and rural area respectively, $p_u = \frac{P_u}{P}$ and $p_r = \frac{P_r}{P}$ stand for the proportion of urban and rural population in the total population respectively.

Then Equations (4) can be expressed as:

$$C = Cf \times Ei \times Rc \times \binom{e_u}{e_r} \times (p_u \ p_r) \times P \quad (5)$$

Take the natural logarithm on both sides and then take the differential to obtain:

$$d\ln C = d\ln Cf + d\ln Ei + d\ln Rc + \frac{d(p_u e_u + p_r e_r)}{p_u e_u + p_r e_r} + d\ln P \quad (6)$$

Let $S_u = \frac{p_u e_u}{p_u e_u + p_r e_r}$, the proportion of urban residents consumption in the whole country is:

$$d\ln C = d\ln(Cf \times Ei \times Rc \times p_u^{S_u} \times p_r^{(1+S_u)} \times e_u^{S_u} \times e_r^{(1-S_u)} \times p) \quad (7)$$

Thus, the continuous product form of carbon emission that can be used for factor decomposition calculation is obtained:

$$C = Cf \times Ei \times Rc \times p_u^{S_u} \times p_r^{(1+S_u)} \times e_u^{S_u} \times e_r^{(1-S_u)} \times p \quad (8)$$

The basic idea of factor decomposition is to decompose the changes of dependent variables in the system into the sum or product of various forms of changes of relevant independent variables, so as to measure the contribution of each variable to the changes of dependent variables. The superscript numbers of 0 and T in the text refer to the base period and calculation period respectively. The addition and decomposition method [28] of logarithmic mean division index (LMDI) is used to decompose equation (8) and the expression of the influence effect of each factor on carbon emission is obtained as follows:

Population size effect:

$$\Delta C_p = \frac{C^T - C^0}{lnC^T - lnC^0} \times ln\frac{p^T}{p^0} \quad (9)$$

Urbanization effect:

$$\Delta C_u = \frac{C^T - C^0}{lnC^T - lnC^0} \times \left[S_u^0 ln\frac{{p_u}^T}{{p_u}^0} + (1 - S_u^0) ln\frac{{p_r}^T}{{p_r}^0}\right] \quad (10)$$

Residential consumption effect:

$$\Delta C_e = \frac{C^T - C^0}{lnC^T - lnC^0} \times \left[S_u^0 ln\frac{{e_u}^T}{{e_u}^0} + (1 - S_u^0) ln\frac{{e_r}^T}{{e_r}^0}\right] \quad (11)$$

Consumption restraint effect:

$$\Delta C_{RC} = \frac{C^T - C^0}{lnC^T - lnC^0} \times ln\frac{{R_c}^T}{{R_c}^0} \quad (12)$$

Energy intensity effect:

$$\Delta C_{Ei} = \frac{C^T - C^0}{lnC^T - lnC^0} \times ln\frac{{E_i}^T}{{E_i}^0} \quad (13)$$

Emission coefficient effect:

$$\Delta C_{cf} = \frac{C^T - C^0}{lnC^T - lnC^0} \times ln\frac{cf^T}{cf^0} \quad (14)$$

Total effect:

$$\Delta C = C^T - C^0 = \Delta C_p + \Delta C_u + \Delta C_e + \Delta C_{RC} + \Delta C_{Ei} + \Delta C_{cf} \quad (15)$$

Equations (10) and (11) don't have S_u^T only then S_u^0. It adopts approximate method. For the differential variation, S_u is actually based on the point elasticity value of origin period. The change of adjacent years is very small, that is to say, it can be treated as approximate equality between S_u^0 and S_u^T. Accordingly, the change effect of non-adjacent years can be obtained by the sum of the change effects of adjacent years between period 0 and period T. The actual calculation results also show the approximate treatment is of rationality.

Results and Discussion

The Impacts of Residential Consumption on Carbon Emissions

The variables of population structure and consumption of urban-rural residents are included in the scope of investigation by expanding the vector form of Kaya identity, and having the aid of logarithmic and differential transformation and LMDI method, the change of carbon emission is divided into six effects, such as population size, population urbanization, residential consumption, consumption restraint, energy intensity and emission factors. Therefore, the decomposition of carbon emission factors is realized in urban and rural areas based on time series data. The calculated and sorted time series data are shown in Table 1.

Based on the above data, factor decomposition calculation of LMDI is carried out by applying Equations (9)-(15), and the decomposition results are shown in Fig. 1.

According to the calculated results, China's carbon emissions increased from 1.448 billion tons to 9.899 billion tons from 1980 to 2020, with the increase of 5.84 times. It is examined that the population and consumption related factors have positive effects on the change of China's carbon emission at this stage, the contribution value of residential consumption factor is the largest, which is 12.781 billion tons of carbon. The second factor is urbanization, which is 3.299 billion tons of carbon; Population size and consumption restraint factors are 0.805 billion tons of carbon and 0.521 billion tons of carbon respectively. The two technical factors - energy intensity and emission factor show negative effects on the whole. The contribution value of energy intensity factor is -8.354 billion tons

Table 1. Urbanization, residential consumption and carbon emissions in China from 1980 to 2020.

Year	Carbon emissions (10^8 tce)	Energy Consumption and Its Composition (10^8 tce)	Population (hundred million people)	Population urbanization (%)	Per capita consumption in urban area (yuan)	Per capita consumption in rural area (yuan)	Consumption restraint factor	Energy intensity (tce/10^4yuan)	Emission factor
1980	14.48	6.03	9.87	19.39	490.00	178.40	1.96	13.14	2.40
1985	17.66	7.67	10.59	23.71	749.60	346.00	1.97	8.43	2.30
1990	21.78	9.87	11.43	26.41	1404.30	626.50	2.00	5.23	2.21
1995	27.23	13.12	12.11	29.04	4767.00	1344.50	2.19	2.14	2.08
2000	32.72	14.70	12.67	36.22	6971.60	1917.00	2.14	1.47	2.23
2005	54.01	26.14	13.08	42.99	9637.00	2783.60	2.53	1.40	2.07
2010	79.05	36.06	13.41	49.95	16569.80	4781.60	2.91	0.88	2.19
2011	87.42	38.70	13.49	51.83	19218.50	5879.60	2.86	0.79	2.26
2012	90.81	40.21	13.59	53.10	20868.60	6573.40	2.83	0.75	2.26
2013	95.34	41.69	13.67	54.49	22619.70	7396.60	2.79	0.70	2.29
2014	94.38	42.83	13.76	55.75	24429.90	8365.00	2.72	0.67	2.20
2015	92.65	43.41	13.83	57.33	26118.70	9409.20	2.65	0.63	2.13
2016	92.17	44.15	13.92	58.84	28154.10	10609.00	2.59	0.59	2.09
2017	93.39	45.58	14.00	60.24	30322.70	12145.30	2.59	0.55	2.05
2018	96.21	47.19	14.05	61.50	32482.90	13984.70	2.60	0.51	2.04
2019	98.26	48.75	14.10	62.71	34900.20	15382.40	2.56	0.49	2.02
2020	98.99	49.80	14.12	63.89	34033.00	16062.60	2.62	0.49	1.99

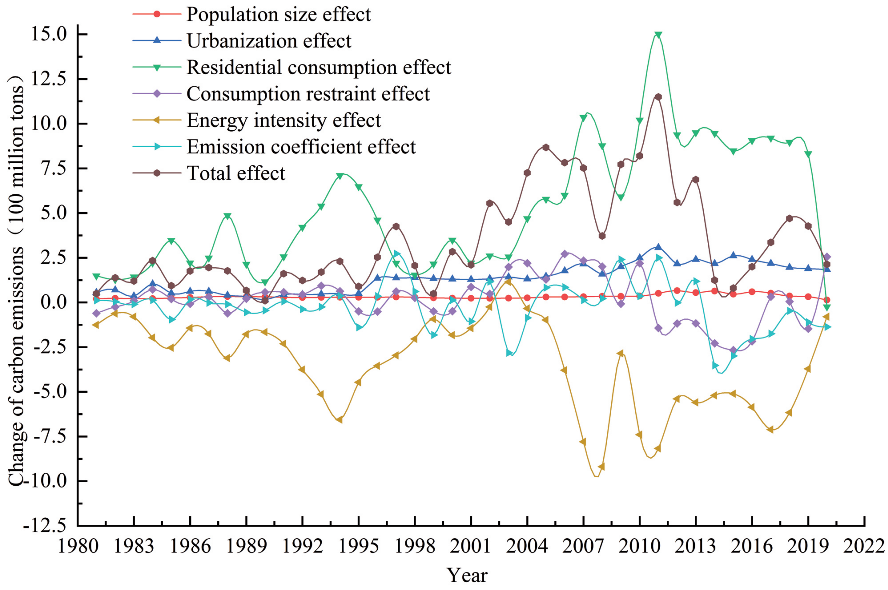

Fig. 1. LMDI Decomposition results for change of carbon emissions. Note: it is calculated and sorted according to China Statistical Yearbook and China energy statistical yearbook over the years. The price is converted according to the unified economic data in 2000.

of carbon, which is the largest emission reduction factor; the contribution value of emission factor is -0.594 billion tons of carbon, which shows a weak negative effect.

According to the absolute value of the contribution rate, we can get the contribution rate of various influencing factors to China's carbon emission growth based on the decomposition analysis from 1980 to 2020. The contribution rates of the six factors examined in the model to the change of China's carbon emission at this stage are as follows: residential consumption effect is 151.24%, urbanization effect is 39.03%, population size effect is 9.53%, consumption restrain effect is 6.16%, emission coefficient effect is -7.03% and energy intensity effect is -98.86%. The decomposition results are analyzed from the perspectives of population, urbanization, residential consumption and technological progress.

The Impacts of Population Size, Urbanization on Carbon Emissions

The annual contribution of population size to carbon emission changes fluctuates slightly between 20 and 66 million tons of carbon dioxide from 1980 to 2020. The contribution value of urbanization has been accelerated after 1996, reaching 307 million tons of carbon in 2011, which is six times of the population scale effect. It can be seen that the driving force of China's urbanization on carbon emissions has greatly exceeded the impact of population size since the middle 1990s. The total population of China increased from 987 million to 1.412 billion from 1980 to 2020, an increase of 43.06%. The annual population growth rate fluctuated and decreased from about 1.25% in the 1980s to about 0.31% in recent years. At the same time, China's urbanization process has been accelerating, and the population urbanization rate has increased from 19.39% in 1980 to 63.89% in 2020.The urban population increased from 191 million to 902 million, an increase of 3.72 times (Fig. 2). Throughout the process of population urbanization, the year of 1995 was an important turning point. In 1995, the rural population reached the historical maximum of 859 million, and then continued to decline. The urban population has continued to increase with an annual increase of more than 20 million people since 1995, and the urbanization process has entered the fast lane.

This change characteristic is basically consistent with the decomposition result that the contribution value of population urbanization to carbon emissions has increased significantly after 1996. It can be seen from the decomposition results that the changes of population size and urbanization rate have a positive effect on the growth of carbon emissions, but their contribution value is far less than that of residential consumption.

The Impacts of Consumption of Urban and Rural Residents on Carbon Emissions

The contribution of changes in carbon emissions and consumption of urban and rural residents in 2020 is shown in Fig. 3. Over the past 40 years, the contribution of China's residential consumption on carbon emissions is much higher than other factors investigated by the model, and stage characteristics is also obvious. Before 2000, the contribution value of most years fluctuated between 20 and 60 million tons of carbon; From 2001 to 2011, it entered a period of rapid growth, the maximum value was 150.2 million tons of carbon in 2011.

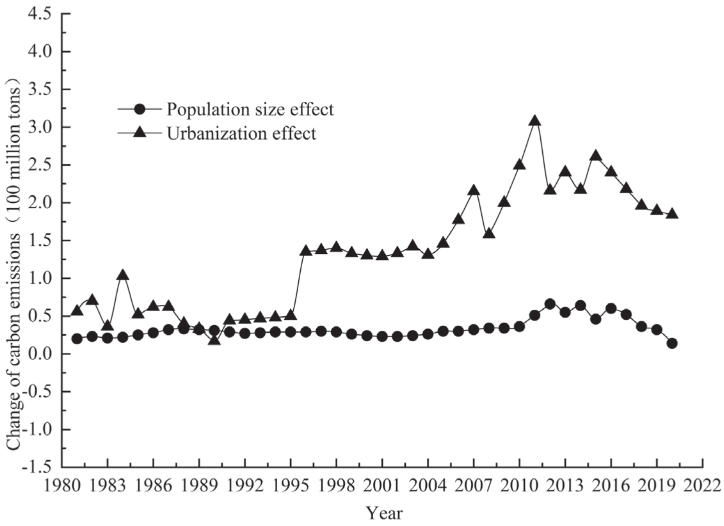

Fig. 2. Contribution of population size and population urbanization to changes in carbon emissions.

After ten years of high-level operation, it fell sharply to 24 million tons of carbon below urban-rural average in 2020. The impact of urban and rural residential consumption on carbon emission changes shows obvious differences. The annual contribution value of rural residential consumption to the change of carbon emission at this stage has always fluctuated around 20 million tons, with the maximum value in 2011, but with the minimum value in 2020.

The impact trend of urban residential consumption on carbon emissions is basically consistent with the national trend without distinction between urban and rural areas, and the gap with the national level is about 20 million tons of carbon. Comparing the urban and rural effects, it can be seen that except for the individual years before the mid-1980s, the impact of urban residential consumption on carbon emissions is greater than that of rural residents. The contribution value in the late 2000s is about 4 times that of the latter, and it fell sharply after 2011.

The per capita consumption of Chinese residents has increased from 238.2 yuan to 27437.9 yuan from 1980 to 2020, an increase of 114 times. The total consumption of urban residents exceeded that of rural residents for the first time in 1990; the per capita consumption of urban residents has always been higher than that of rural residents, and the gap has been expanding since the mid-1980s. The per capita consumption ratio between urban and rural residents was 3.87 in 2010, decreased after 2011 and it was 2.12 in 2020. The carbon emission caused by residential consumption is generally divided into two aspects: one is the direct carbon emission

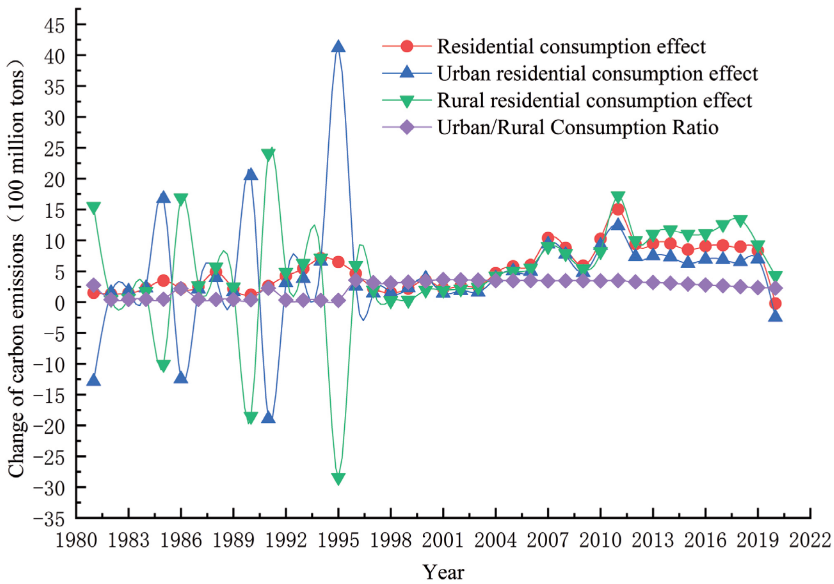

Fig. 3. Contribution of urban and rural residential consumption to changes in carbon emissions.

generated by residential families in domestic energy consumption such as cooking, hot water and heating; Second, the indirect carbon emissions caused by the energy consumption carried by consumer goods in their raw materials, production, transportation and sales, that is, the energy carrying carbon emissions of consumer goods. The latter reflects the sum of carbon emissions generated by the energy consumption of various industrial sectors in the life cycle of consumer goods, the change of carbon emissions measured from the perspective of residential consumption actually includes the impact of production activities.

Since previous research shows that the proportion of carbon emissions from domestic energy consumption in China's total carbon emissions from energy consumption was 9.9%-18.0% from 1980 to 2007; the energy carrying carbon emissions of consumer goods accounted for 58.7%-64.3% of the total emissions from 1992 to 2005 [29]. The carbon emissions caused by residential consumption (including direct and indirect emissions) account for 70% - 80% of the total national emissions. It can be seen that the impact of residential consumption on carbon emissions is much higher than the share of residential consumption in GDP. From the comparison between urban and rural areas, since the 1980s, the per capita carbon emission of urban residential domestic energy consumption has generally shown a fluctuating downward trend, and the urban-rural ratio of carbon emission of per capita domestic energy consumption has also shrunk from 3.58 to about 0.27. The agglomeration effect and scale effect of urban population in domestic energy consumption and its carbon emission have appeared. On the other hand, the urban-rural gap of energy carrying carbon emission of consumer goods is increasing, and the per capita urban-rural ratio in recent years is about 4.0. Therefore, it can be considered that the impact of China's residential consumption on carbon emissions at this stage mainly comes from the continuous increase of energy carrying carbon emissions of urban residential consumer goods.

The Impacts of Consumption Restraint Factors on Carbon Emissions

Although the change of residential consumption on China's carbon emissions at this stage has always shown a positive effect, the change of consumption restraint factors represented by the ratio of GDP to residential consumption has not always had a positive effect on carbon emissions. In most years, its contribution value is positive, reaching a maximum of 271 million tons of carbon in 2006. According to the measurement definition of GDP, GDP is the sum of residential consumption, government consumption, fixed asset investment and net export. Therefore, under the given conditions of GDP, the ratio of GDP to residential consumption changes inversely with residential consumption and in the same direction with the sum of government consumption, investment and net export, which actually represents the restraint degree of the economy on residential consumption. Since the consumption rate of Chinese residents has fluctuated from about 55% in recent 40 years to about 40% in recent years, the consumption restraint factors have continued to rise on the whole, highlighting the weakness of domestic demand in China's economic growth. The impact of consumption restraint factors on carbon emissions is generally positive, indicating that the synchronous increase of the proportion of government consumption, investment and net export in the economic component plays a driving role in the growth of carbon emissions. Because the difference of contribution value of different economic components to carbon emission mainly comes from the difference of carbon emission intensity, the above empirical results actually reflect that the carbon emission intensity of the consumer goods industry sector is generally lower than that of other economic components. Under the condition that the scale of economic output is fixed, restraining residential consumption means encouraging government consumption, investment and export. As a result, it encourages the development of economic components with high emission intensity, which further stimulates the growth of China's carbon emissions. It can be seen that there is an internal logic of reverse change between China's residential consumption rate and carbon emission at this stage, which also explains that the years in which the residential consumption rate decreased significantly, were accompanied by a significant increase in carbon emission.

The Impacts of Energy Intensity and Emission Factors on Carbon Emission

There are two important indicators of energy technological progress. The changes of energy intensity and emission factors on China's carbon emission generally show a negative effect (Fig. 4), highlighting the important role of technological progress in controlling carbon emission. Since the emission coefficients of different types of fossil energy are calculated as constants in the study, the impact of emission factors on carbon emissions mainly depends on the change of energy structure. According to the data of China energy statistical yearbook from 1980 to 2020, the proportion of coal and oil in China's primary energy consumption reduced from 69.4% to 67.5% and from 23.8% to 6.8%, namely decreased by 1.9 and 17.0 percentage points respectively, and the proportion of natural gas and non-fossil energy (mainly hydropower and nuclear power) increased by 3.0 and 15.9 percentage points respectively. Although the energy source structure has been optimized, the change range is small. Accordingly, the contribution value of emission factors to the change of carbon emission showed a slight downward trend, which reduced from 2.4 to 1.99 million tons of carbon from 1980 to 2020. Energy intensity has a significant negative effect on the

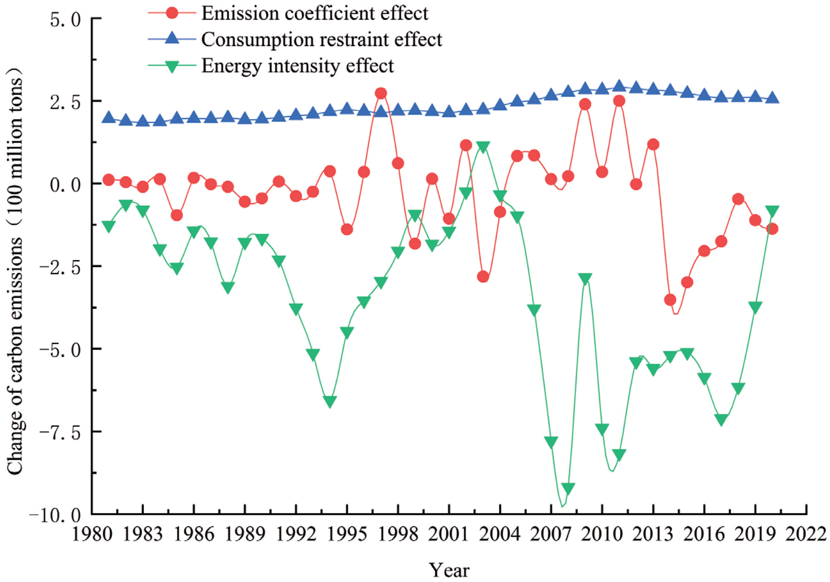

Fig. 4. Contribution value of energy intensity and emission factors to carbon emission change.

change of carbon emissions. Except for a short rebound in 2003,2009 and 2020, the contribution values in other years are significantly negative and the absolute value is increasing. This trend is basically consistent with the continuous reduction of China's energy intensity at this stage. From 1980 to 2020, China's energy intensity fluctuated from 13.14 t standard coal/10^4 yuan to 0.49 t standard coal/10^4 yuan. An obvious rebound is taking place in 2003, 2009 and 2020. In recent years, with the increasing efforts of energy conservation and emission reduction at the policy level, energy efficiency has improved significantly, and its negative effect on carbon emission has also been increasing.

Since the carbon emission intensity is equal to the product of energy intensity and emission factor in quantitative relationship, the contribution of carbon emission intensity change to carbon emission is equal to the superposition of energy intensity effect and emission factor effect. It can be inferred that the improvement of China's carbon emission intensity in recent 40 years mainly comes from the decline of energy intensity, and the emission reduction effect of energy structure adjustment is very limited. In the past 40 years, the growth of the contribution of residential consumption to carbon emissions is much lower than that of consumption, mainly due to the continuous decline of carbon emission intensity, especially energy intensity.

Conclusions

By expanding the vector form of Kaya identity, this paper includes variables such as population urban-rural structure and urban-rural residential consumption; LMDI method is used to quantitatively evaluate the impact of residential consumption and other factors on carbon emissions driven by urbanization in China in recent 40 years, and measure the contribution rate and variation characteristics of each influencing factor. This study effectively overcomes the limitations of data availability and inspection cycle in the decomposition analysis based on input-output table in the existing research. The main conclusions are as follows:

Considering the effects of six factors, such as population size, urbanization, residential consumption, consumption restraint, energy intensity and emission factors, from 1980 to 2020, the contribution rate of residential consumption to carbon emission growth in China was much higher than the other five effects. From the perspective of consumption, the improvement of urban residential consumption level and the expansion of consumption scale are the main driving forces of China's carbon emission growth since the middle of 1980.

Taking the mid-1990s as the turning point, before that, the contribution rate of China's population expansion to the growth of carbon emissions was higher than that of population urbanization; since then, the driving force of population urbanization on carbon emission growth continues to exceed the impact of population size, and the growth rate has been increasing in recent years.

The consumption restraint factors represented by the reciprocal of residential consumption rate have a positive effect on the growth of China's carbon emission in recent 40 years, indicating that the carbon emission intensity of economic components such as government consumption, fixed asset investment and export is higher than that of residential consumption, and the reduction of residential consumption rate has a greater driving effect on carbon emission than restraint.

Over the past 40 years, the contribution of residential consumption to carbon emission growth has increased much lower than that of consumption, mainly due to the continuous decline of carbon emission intensity, especially energy intensity, and the emission reduction effect of energy structure adjustment has not been significantly reflected.

It should be noted that this paper decomposes the change of carbon emission into six factor effects, which does not mean that carbon emission is only related to these six factors. This paper examines the impact of urbanization on carbon emissions from the perspective of residential consumption, mainly by analyzing the impact of urban and rural population changes and urban and rural residential consumption changes on carbon emissions, while the impact of urbanization through other channels is not clearly distinguished from the indicators. However, this does not mean that emissions are only related to consumption and deny the impact of production activities. In fact, under the condition of relative balance between production and consumption, the change of consumption reflects the change of production at the same time. From the perspective of consumption, it can also indirectly reflect the impact of the change of production on carbon emissions. Similarly, this impact is also reflected in the consumption restraint, energy intensity, emission factors and other effects decomposed in this paper. Different research perspectives correspond to different deformation and decomposition methods of Kaya identity, which determines the category of the factors investigated.

Acknowledgments

This research was sponsored by the Natural Science Foundation of Henan Province of China (Grant No. 182300410114). The support is gratefully acknowledged. Many thanks to the anonymous reviewers whose interesting comments were helpful in improving the quality of this paper.

Conflicts of Interest

The authors declare no conflict of interest.

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