EXPLORING THE ROLE OF ENERGY CONSUMPTION AND POPULATION AGING IN CARBON EMISSIONS IN THE CONTEXT OF LOW CARBON DEVELOPMENT IN CHINA

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Abstract. Coping with and mitigate the impact of population ageing and actively promote the timely realization of the “two-carbon” goal, it has become a topic of concern. The study uses 30 regions of China, and selects the period of 2008-2023 to explore the influence mechanism of population aging on carbon emissions (CE), explores whether the relationship is nonlinear through the threshold effect model, and further clarify the inflection point value of the nonlinear relationship, and draws the conclusions as follows: (1) The effect of population aging is negative, which confirms that the degree of and aging also affects the total amount of CE, showing a significant inhibitory effect. Population aging can improve the control of CE. (2) Non-linear relationship exists between population aging and CE, which confirms the existence of a single threshold, the estimated value of which is -1.633. Regardless of whether the degree of aging is greater than -1.633 or not, population aging suppresses CE and the larger the coefficient, the more pronounced the suppression effect will be. (3) Population aging increases CE by promoting energy consumption, which confirms the existence of the mediating effect.
Keywords: *sustainable development, low carbon economy, carbon neutrality, energy transition, global warming*

Introduction

With global warming and environmental pollution problems becoming more and more prominent, the green transformation of energy is getting an increasing attention. Since China’s reform and opening up, the traditional energy industry has been developed greatly. A number of coal industry indicators have contributed primarily to social and economic development in China for many consecutive years. However, such development has come at a high environmental and resource cost, causing serious challenges to high-quality economic growth. For example, reliance on traditional energy sources has resulted in substantial CE, significantly hindering China in reaching carbon neutrality. As a result, the transition to green energy has become a critical path for sustainable development in the region (Rzymski et al., 2024). CE are the main cause of the greenhouse effect, global CE reached 37.4 billion tons in 2023, an increase of 410 million tons, or 1.1%, compared with 2022, and China’s CO_2 emissions were 12.6 billion tons of carbon dioxide equivalent in 2023, an increase of 4.13% compared with 12.1 billion tons in 2022. The increase in CE leads to various environmental problems and brings great negative impacts on people’s lives, thus it is increasingly important to study CE.

Energy consumption plays an important role in the study of CE. Coal and crude oil are the main sources of CE and environmental pollution, accounting for the largest part

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of China’s total energy consumption (Ouattara and Kouakou, 2024). In addition, household energy consumption accounts for a significant portion of total energy consumption. Similarly, it has a significant impact on CE and environmental pollution. Currently household consumption contributes about 67% of the total global greenhouse gas emissions. The role of demographic factors in CE is becoming increasingly significant. The population problem is not only a problem of large numbers, but also a structural problem. China entered aging society since 2000, Chian pointed out that China’s working-age population aged 16-59 years old will be 864.81 million, accounting for 61.3%; the population aged 60 years old and above, accounting for 21.1% of the national population, and 65 years old and above, accounting for 15.4% (Li and Jiang, 2023). The United Nations suggests in World Population Prospects Report (2019.6.17) that by 2041, the degree of aging may exceed 30%, entering a heavily aging society and becoming one of the countries with the highest degree of aging in the world. The size of China’s aging population and the speed of aging are unprecedented. Since human production and consumption are directly affected by the age structure, and production and consumption affect end-use energy consumption and thus aging will affect CE, and aging will cause a shortage of effective labor supply, which will slow down the economic growth, and due to the positive correlation between economic growth and CE (Xia, 2019), aging will lead to a decrease in energy and CE. Yu et al. (2022) concluded that the indirect CE peak in the age group of 20 years old and gradually decline with the growth of age. Since the indirect emissions of carbon dioxide from elderly households are relatively low, population aging will reduce the indirect emissions of carbon dioxide in the future. Therefore, it is uncertain whether ageing will lead to an increase or decrease in CE, but it is certain that ageing will definitely have an impact on CE.

In the stage of population aging, in order to achieve healthy and sustainable development, economic growth must get rid of dependence on labor-intensive industries, improve the economic structure of output through the improvement of labor quality, and accelerate industrial structure upgrading (Wang and Wang, 2020). Under the pressure of CE reduction, clarifying how the demographic structure affects household energy consumption will help the public to save energy and reduce emissions by reducing household energy consumption in daily life (Tang et al., 2024). Based on this, this paper takes 30 regions (provinces, autonomous regions and municipalities) in China as the research space unit, and selects the time period of 2008-2023. The main purpose of this paper is to analyze the mechanism of the impact of population aging on carbon emission, and verify the mediating effect of energy consumption, so as to provide valuable information for the current more accurate understanding of population aging and energy consumption, as well as to better reach the carbon emission reduction target of China’s “30, 60” and promote the high-quality development of economy. It also provides valuable references for a more accurate understanding of population aging and energy consumption, as well as a better way to achieve China’s “30, 60” carbon emission reduction target and promote high-quality economic development.

Literature review

Population aging impact on CE

With the acceleration of the global aging process, exploring the relationship between aging and CE has become a new academic perspective. Some scholars study

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relationship between population size and CE (Yan et al., 2023; Albrecht et al., 2002; Puliafito et al., 2008; Yang and Yang, 2018). Dalton et al. (2008) explored population aging impact on CE from 2000 to 2010 and shown that population aging could reduce CE in the U.S.; under certain circumstances, this reduction effect is even significantly stronger than that of technological factors. O'neill et al. (2010) found that aging can reduce CE by as much as 20%, especially in industrialized countries, mainly through the impact on labor supply to affect CE. Hassan and Salim (2015) showed that a 1% increase in population ageing reduces per capita CO_2 emissions by 1.55%, and Liddle and Lung (2010) found that the 65-70 age group has an effect of increasing CE by examining the environmental impacts of different age groups. Menz and Welsch (2010) studied 26 countries of OECD in 1960-2005 and got the same conclusion. Domestic scholars Liu (2023) found that the mediating effect of working-age population is not significant in the sample period. Cui (2023) found that the impact of aging on CE has spatial and temporal heterogeneity, and in the time dimension, it shows a phase characteristic, and the impact relationship has changed from a facilitating effect to an inhibiting effect; in the spatial dimension, it shows a ladder characteristic of "central-western-eastern" decreasing in order, and contrary to the facilitating effect in central and western China, the eastern region has already demonstrated the mitigating tendency of aging on CE. Xu (2017) found that in the early stage of population aging, aging will significantly increase CE, but when aging reaches a certain level, it will have a suppressive effect on CE. However, some scholars found an N-shaped relationship between aging and CE (2018).

Population aging impact on energy consumption

Aging changes the structure of domestic energy consumption, for example, population aging reduces energy consumption demand in the transportation and communication categories (Prskawetz et al., 2004), but at the same time increases energy consumption for lighting and heating in housing (O'Neill and Chen, 2002). Thus, overall, the impact of aging on the level of per capita domestic energy consumption varies. Among empirical studies, Yamasaki and Tominaga (1997) found that aging increases per capita domestic energy consumption, which partly stems from the fact that the elderly spend more time at home and that government subsidy policies promote greater use of household appliances by the elderly. Shen and Qi (2018) concluded that population aging significantly increases per capita domestic energy use, which in turn negatively affects CE. However, a study by Zhang and Xu (2011), based on survey data from rural households in Shanxi and Jiangsu, found that the domestic electricity consumption of households with elderly people was significantly lower than that of households without elderly people, which may be due to the fact that elderly people in rural areas live a relatively monotonous life and are more accustomed to the use of traditional biomass energy sources. Guo and Sun (2017) argued that the consumption level of the elderly group is lower compared to the younger population because of their declining level of energy consumption, which reduces the need for energy. Dalton et al. (2006) based on the data on energy consumption of various age groups in the United States, showed that the level of population aging is negatively correlated with the energy consumption under the lesser pressure of old-age pensions. Chen et al. (1999) analyzed from the perspective of resource cost transfer and concluded that a higher old-age dependency ratio in an aging society would force people to pay more attention to economic development and neglect the conservation and intergenerational transfer of energy.

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Energy consumption impact on CE

Economic growth, energy consumption and carbon dioxide emissions are the focus of academic research today. Many scholars have studied the relationship between energy consumption and carbon dioxide emissions, and the research methods mainly focus on the cointegration test and Granger causality test. Soytas et al. (2007) took the U.S. gross domestic product (GDP), energy consumption, and carbon dioxide emissions for the period of 1960-2004 as the sample data, and combine the Granger causality test, the prediction of variance decomposition analysis and other technical means to empirically investigate the dynamic relationship between them. Soytas and Sari (2009) used Granger causality test to investigate the dynamics of GDP, energy consumption and CO_2 emissions in Turkey from 1960 to 2000, and concluded that there is no directional Granger causality between CE and energy consumption, but a unidirectional causality from energy consumption to CO_2 emissions; Apergis (2009) examined the carbon dioxide emissions, energy consumption, and production of France by using a panel vector error correction model. The study shows that the French economy and CE are consistent with the “EKC” hypothesis. In the long run, there is a bidirectional causal relationship between energy consumption and CE. Wang et al. (2020) assessed the potential contribution of optimization of energy consumption structure to CE intensity in Hebei province under different combinations of scenarios, and the empirical evidence shows that no matter what combination of scenarios is used, the optimization of energy consumption structure can promote the reduction of CE intensity to varying degrees, and contribute to the realization of CE reduction targets. Wei (2019) used a fixed-effects model to analyze the impact mechanism of energy consumption scale on CE, and the results show that coal consumption is the main reason for the continuous increase of CE intensity.

In summary, through summarizing the relevant literature, we can find that there are more studies on these topics, but the relationship between the three has not been fully explored. It is important to explore the impacts of population aging and energy consumption on CE. At the level of corresponding regional CE, the in-depth investigation of the transmission mechanism of population aging and energy consumption on CE has been neglected, and the analysis of some indirect mechanisms related to the three is missing. Therefore, it needs to explore their possible correlation effects and non-linear relationships, so as to provide valuable references for a more accurate understanding of population aging, as well as to better achieve China’s “30, 60” CE reduction targets and promote high-quality economic development.

Methodology

Modeling the direct impact of population aging on CE

Improved STIRPAT model proposed by Ehrlich and Holdren (1971), conceptualized the impact of various human socio-economic activities on environmental pressures, the IPAT model expression is:

$$I = PAT \tag{Eq.1}$$

where I, P, A, and T denote the environmental pressure impact, population size, affluence, and technology level, respectively. The model cleverly links the

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environmental pressure impact with the three types of influencing factors, namely, population size, affluence, and technology level, in the form of extremely simple and intuitive setting, which is recognized and applied by a large number of scientific researchers in the academic world.

Dietz and Rosa (1994) modified the IPAT model and established the STIRPAT model, its model expression is:

$$I = aP^bA^cT^d\varepsilon \tag{Eq.2}$$

In *Equation 2*, I, P, A, and T are still denote the impact of environmental pressures, the population size, the degree of affluence, and the level of technology, respectively; a is the model constant term, b, c d are the estimated indices of population size, affluence, and technology level, respectively, and ε is the model random error term. From the model form, it can be seen that the STIRPAT model is equivalent to the IPAT model when $a = b = c = d = 1$. The introduction of the estimation indices allows the STIRPAT model to be used to analyze the non-homogeneous proportionality of the effects of the factors on the environment (Wang and Zhou, 2012; Payaga et al., 2022). If logarithms are taken on both sides of the STIRPAT equation, the relationship between environmental stress and each influencing factor can be transformed into a linear relationship, i.e.:

$$lnI = lna + blnP + clnA + dlnT + ln\varepsilon \tag{Eq.3}$$

In *Equation 3*, the regression coefficients b, c, and d express the elasticity coefficients between the environmental pressure and each influencing factor, i.e., the percentage change in the environmental pressure caused by a 1% increase in an influencing factor. The model and its various extended forms have been widely used in CE studies at home and abroad. The consumption of fossil energy was used to calculate the CE of each regions by using the formula.

$$C_{it} = \sum_{x=1}^{k}(E_{ixt} \times \sigma_x \times \rho_x) \times 44/12 \tag{Eq.4}$$

where: C_{it}denotes the CE of regions, E_{ixt} denotes the total consumption of energy, σ_x denotes the reference coefficient of energy conversion to standard coal, ρ_x denotes the CE coefficient of energy type x, which is derived from the conversion coefficient of standard coal published in the IPCC.

$$\mathrm{CO_2} = \sum_{\mathrm{i=1}}^{\mathrm{n}}(\mathrm{A_i} \times \mathrm{B_i} \times \mathrm{C_i}) \tag{Eq.5}$$

where A_i indicates the consumption of the i-th energy source, B_i indicates the CE coefficient of the ith energy source, C_i indicates the standard coal conversion coefficient of the ith energy source, n indicates the number of energy sources to be involved in the calculation, and this paper selects the commonly used nine energy sources for calculation.

Modeling the threshold effect of population aging on CE

This paper further in-depth research on studying population aging impact on CE. As far as the specific form of society is concerned, the elderly population always occupies a certain proportion in society, and within a specific range, the increase or decrease of the

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elderly population does not have an impact on the economy and society or has a small impact, but when elderly population reaches a certain level, the impact on the economy and society begins to show and increase, and the impact on CE is also the same. Therefore, it is necessary to carry out the test of threshold model, when the population aging reaches the threshold value will have any different impact on CE. In the study, the threshold regression model proposed is used (Hansen, 2000). The single threshold regression as follows:

$$y_{it} = \beta_0 + \beta_1 X_{it} I(q_{it} \le \eta) + \beta_2 X_{it} I(q_{it} > \eta) + \beta_3 Z_{it} + \mu_{it} \quad \text{(Eq.6)}$$

In *Equation 6*, y_{it} is explained variable, X_{it} is core explanatory variable, Z_{it} is control variable, I(·) is indicator variable, q_{it} threshold variable, and η threshold value.

If $q_{it} \le \eta$, I($q_{it} \le \eta$) = 1, I($q_{it} > \eta$) = 0; if $q_{it} > \eta$, I($q_{it} \le \eta$) = 0, I($q_{it} > \eta$) = 1.(Eq.7)

When estimating the model (*Eq. 6*), it is first necessary to determine the size of the threshold η, the observed values of the threshold variables are first brought into the model, and the least squares regression is performed to obtain the residual sum of squares SSR(η), at which time the threshold value corresponding to the smallest residual sum of squares is selected as the true threshold value, i.e., η = argminSSR(η). The significance test of the threshold effect is also needed after estimating the threshold value. The original hypothesis is H0: β1 = β2, which indicates that there is no threshold effect; the alternative hypothesis is H1: β1≠ β2, which indicates that β1 and β2 have different effects in the two intervals. The residual sum of squares obtained under the original hypothesis is denoted as S0, and the residual sum of squares obtained under the alternative hypothesis is denoted as S1, and the likelihood ratio statistic $LR = \frac{(S_0 - S_1(\eta^*))}{\sigma^2}$ where $\sigma^2 = \frac{S_1(\eta^*)}{\mathrm{n}(T-1)}$. The non-standardization of the LR statistic is caused by the interference of the uncertainty of the threshold under the original hypothesis. In order to effectively overcome this problem, this paper uses the "self-help sampling method" to transform the asymptotically valid P-value under a large sample, and gives the formula for calculating the rejection domain, under the significance level α, if $LR(\eta^*) > -2\log(1 - \sqrt{1-\alpha})$, the original hypothesis is rejected; on the contrary, it does not reject the original hypothesis. The above is the case of the existence of a single threshold, in practice there will be multiple thresholds. Multiple threshold regression model construction and testing principle is similar to the above situation, will not repeat here.

According to the characteristics of the above threshold regression model, take a single threshold as an example, combined with the variables, the threshold regression model is constructed as follows.

$$CI_{it} = \beta_0 + \beta_1 lnAG_{it} I(lnAG \le \eta) + \beta_2 lnAG_{it} I(AG > \eta) + \gamma_{it} lnZ_{it} + \mu_{it} \quad \text{(Eq.8)}$$

where CI_{it} is per capita CE, $lnAG_{it}$ is population aging, lnZ_{it} is other variables, and the other variables are explained in *Equation 6*, μ_{it} is the stochastic perturbation term.

Modeling the mediating effect of population aging on CE

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Population aging can play a role in regional CE reduction through the important channel of energy consumption, population aging and energy consumption can have a significant impact on regional CE, and the deepening of the degree of population aging is directly related to the supply of labor in the market, changes in the structure of human capital, as well as the consumption of the residential sector and the production of the enterprise sector, which are all complementary with energy consumption, and thus have an important indirect effect on CE. All these are complementary to energy consumption, and thus have an important indirect impact on CE, so it needs to analyze the influence of energy consumption on regional CE due to population aging.

For further confirming whether energy consumption has a mediating effect, the work constructs a mediating effect model to test. Drawing on the practice of He and Li (2020), this paper also adopts mediation effect model, and constructs the recursive equations as follows:

$$\mathrm{CI}_{it} = \mathrm{A} + \mathrm{c}_2\mathrm{AG}_{it} + \sum\delta_i\mathrm{Z}_{it} + \varepsilon_{it} \tag{Eq.9}$$

$$\mathrm{ES}_{it} = \mathrm{B} + \mathrm{aAG}_{it} + \sum\delta_i\mathrm{Z}_{it} + \varepsilon_{it} \tag{Eq.10}$$

$$\mathrm{EQ}_{it} = \mathrm{C} + \mathrm{c}_1\mathrm{AG}_{it} + \mathrm{bES}_{it} + \sum\delta_i\mathrm{Z}_{it} + \varepsilon_{it} \tag{Eq.11}$$

In *Equations 10–11*, A, B, C are constant terms, ε_{it} is a random disturbance term, and $\sum\delta_i Z_{it}$ denotes the sum of the products of control variables and their regression coefficients. CI_{it} denotes CE, AG_{it} indicates population ageing, and ES_{it} denotes the mediating variables. *Equation 9* is to test whether aging has a significant effect on CE, and the impact coefficient is denoted as c_2; *Equation 10* is designed to test whether there is a significant effect of aging on energy consumption, and the impact coefficient is denoted as *a*; *Equation 11* is to explore whether aging and energy consumption have a significant effect on CE at the same time, and c_1 and b are the impact coefficients of aging and energy consumption, respectively. If the coefficients *a*, *b*, and c_2 are all significant, it indicates that energy consumption has a mediating effect in the relationship. Further test the coefficient c_1, if c_1 is not significant, it means that there is only mediating effect that is complete mediating effect; if c_1 is significant, it means that there is partial mediating effect. Finally, Bootstrap method is used to test the robustness of the mediation effect and calculate the proportion of the mediation effect to the total effect according to the formula ab/c_2.

Selection of explanatory variables

(1) Population perspective

Urbanization (UR). Population urbanization rate in China continues to rise, environmental problems have become more and more serious. Wang and Zhou (2012) believed that with the acceleration of urbanization, a large number of urban infrastructure is essential, and this work will inevitably lead to a large amount of raw material consumption, which will lead to an increase in CE, and as the level of urbanization becomes higher and higher, people's lifestyles and habits also change due to it, especially promoting the use of important energy sources such as oil, which will

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undoubtedly increase the total amount of CE. In the study, the proportion of urban population to total population is selected to represent population urbanization.

Population aging (AG). Many scholars feel that the higher level of aging will hinder the economic development of China, but also slow down the progress of society, the study of China's economy and society in the context of aging is of great significance. The age of 65 and above belongs to the old population, therefore, adopting the common practice in the literature, the percentage of population aged 65 and above is used as an indicator to measure population of each regions, and the population aging in each region is further characterized by the elderly population dependency ratio.

(2) Wealth perspective

Level of economic development (GDP). Nowadays, people's living standards are different from the past, and the consumption level has also risen, and the damage caused by energy consumption to the environment is incalculable, and some environmental problems have gradually appeared. GDP per capita can reflect the level of wealth of the residents of the region or country, therefore, this paper chooses this indicator to represent wealth in the model and explore its impact on CE.

The degree of openness to the outside world (OP). With the increase in the degree of opening up to the outside world, advanced production technology and management experience can be continuously introduced, which will have a spillover effect on the high level of green development of regional industry, thus enabling the transformation of its industrial production mode, eliminating backward production capacity, optimizing the industrial structure, and thus enhancing the carbon emission reduction capacity of regional industrial development, but it is also possible that with the increase in the degree of opening up to the outside world, foreign high-pollution and high-emission industries will be transferred to the country, thus increasing regional carbon emissions. However, with the increase of openness to the outside world, foreign high-pollution and high-emission industries will be transferred to China, which will increase regional carbon emissions. It is expressed as the ratio of the annual import and export amount to the GDP of each region, which is also one of the indispensable factors for exploring carbon dioxide emissions.

(3) Technological perspective

Energy consumption (ES). That is, energy consumption per unit of GDP, is an important indicator used to measure the efficiency of energy utilization. Improvement of technology can effectively inhibit the increase of CE, at present China is in the period of industrialization and development, the energy consumption intensity can well reflect the current level of industrial technology. The lower the energy consumption intensity, the less energy consumed for the same output value, and the lower the CE, so generally speaking, energy consumption intensity and CE should be positively correlated. In this paper, the per capita consumption of domestic energy is calculated in kilograms of standard coal (kgce). The data of domestic energy are all taken from the domestic energy consumption part of the Comprehensive Energy Balance Scale in the statistical yearbooks of each regions. Total energy consumption includes three parts: terminal energy consumption, energy processing and conversion losses and losses. In order to standardize the calibrations and avoid fluctuations in losses caused by differences in energy processing and conversion technologies, terminal energy consumption is used in this paper. In view of the fact that some regions and municipalities have only counted the total consumption of domestic energy, when processing the data, we first calculate the proportion of the consumption of terminal energy in all sectors to the total consumption of energy in all sectors, and then derive the terminal consumption of domestic energy according to the coefficient of this proportion, and the per capita consumption of domestic energy is the terminal consumption of domestic energy divided by the number of permanent residents in the province or municipality.

Level of scientific and technological input (TI). High technology can enhance the level of production technology, improve production efficiency, reduce the total CE, and treat the existing pollutants to achieve CE. However, it is precisely because of more demand for products, so that enterprises in the production of pollutants will produce more. Therefore, science and technology have a great impact on CE, this paper chooses the proportion of local financial science and technology expenditures in the government's financial expenditures to indicate the level of investment in science and technology, and then explore its impact on CE. At the same time, due to the CE and the above factors are not necessarily a linear relationship between the specific relationship needs to be based on the statistical nature of the specific data to be assumed, based on this, the level of per capita CE and the influence of the factors are assumed to be a non-linear function of the form of the improved STIRPAT model general expression for:

$$lnC\mathrm{I} = f1(ln\mathrm{UR}) + f2(ln\mathrm{AG}) + f3(ln\mathrm{GDP}) + f4(ln\mathrm{OP}) + f5(ln\mathrm{ES}) + f6(ln\mathrm{TI}) + \varepsilon \quad \text{(Eq.12)}$$

In *Equation 12*, *CI* represents per capita CE as the explanatory variables of this paper, UR represents urbanization, *AG* represents aging rate, *GDP* represents economic development, *OP* represents opening up to the outside world, *ES* represents energy consumption, and *TI* represents scientific and technological inputs; (i = 1,2,3,4,5) denotes the nonlinear functional form, and ε still represents the model error term. The expression of the regression equation based on the extended STIRPAT model is established as follows:

$$\ln CI_{it} = \ln\alpha_i + \beta_1 \ln\mathrm{UR}_{it} + \beta_2 \ln AG_{it} + \beta_3 \ln\mathrm{GDP}_{it} + \beta_4 \ln\mathrm{OP}_{it} + \beta_5 \ln\mathrm{ES}_{it} + \beta_6 \ln\mathrm{TI}_{it} + \ln\varepsilon_{it} \quad \text{(Eq.13)}$$

where i denotes regions, t represents time, variable elasticity coefficients β_1, β_2, β_3, β_4, β_5, and β_6 are the indicators affecting the CE of each region, respectively elasticity coefficients, $\ln\alpha_i$ denotes the individual effect, and $\ln\varepsilon_{it}$ denotes the random perturbation term of regions *i*.

Results and discussion

Smoothness test

In the process of empirical analysis will often find some unrelated economic series have the same trend, and these time series are often non-smooth, then if the two are regressed, the R^2 obtained is often very large, but the results do not make any sense, that is, there will be a false regression or pseudo-regression. The panel data model constructed in this paper contains time series, so for avoiding the occurrence of pseudo-regression phenomenon, it needs to test the smoothness of data and the most commonly

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used method of smoothness of the unit root test, there are a lot of tests such as the IPS test, Fisher-ADF test, Fisher-PP test, etc. In the work, we use the LLC and Fisher-ADF test to verify, when the two tests are rejected the original hypothesis that the sequence is smooth. *Table 1* reports the results of the tests, which show that the null hypothesis is rejected for the first-order differences of each variable, i.e., there is no unit root in the panel. Therefore, the paper concludes that each variable is a first order smooth series for further regression analysis.

Table 1. *Results of smoothness test*

Variable	LLC test	ADF-Fisher test	First-order difference	LLC test	ADF-Fisher test
lnCI	-2.45 (0.00)	31.93 (1.00)	dlnCI	-15.65 (0.00)	199.65 (0.00)
lnAG	-3.45 9 (0.00)	99.04 (0.00)	dlnAG	-17.65 (0.00)	231.97 (0.00)
lnUR	-5.67 (0.77)	5.444 (1.00)	dlnUR	-34.64 (0.00)	221.43 (0.00)
lnGDP	-7.89 (0.00)	72.78 (0.08)	dlnGDP	-20.18 (0.00)	188.89 (0.00)
lnOP	-3.44 (0.00)	55.65 (0.67)	dlnOP	-9.98 (0.00)	341.57 (0.00)
lnES	-4.35 (0.00)	49.56 (1.00)	dlnES	-44.56 (0.00)	167.87 (0.00)
lnTI	-7.78 (0.00)	80.34 (0.04)	dlnTI	-39.19 (0.00)	289.15 (0.00)

Tests for multicollinearity

Multicollinearity is the phenomenon of high correlation between independent variables in a regression model. Tests include variance inflation factor (VIF), tolerance, eigenroots, conditional exponents, and correlation coefficient matrices. This paper adopts the VIF method used by most scholars, and the test results are shown in the *Table 2*. From the results, the maximum VIF of 4.14 is much smaller than 10, so it can be assumed that there is no significant correlation between the variables, and it can be further regression analysis.

Table 2. *Results of multiple covariance test*

	AG	UR	GDP	OP	ES	TI
VIF	1.56	2.35	4.14	2.55	3.78	2.44

Model selection test

For panel data, it is crucial to utilize an appropriate model. Therefore, before regression analysis of each regions, it is necessary to select the appropriate model. The research tools in this paper all use stata statistical analysis software, in turn, the panel data of each regions Wald test, B-PLM test and hausman test based on bootstrap method, the test results as *Table 3*.

Table 3. *Model selection test results*

Test methods	Statistic	P value	Result
Wald test	31.28	0.0000	Fixed effect
B-PLM test	1598.35	0.0000	Stochastic effect
Hausman Test	0.77	0.987	Stochastic effect

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In *Table 3,* when comparing the models at the national level, the first judgment model should be selected as a mixed regression model or a fixed effects model, which is significant at the 1% significance level and rejects the original hypothesis, so the fixed effects model is selected; when comparing the mixed regression model with the random effects model, which is significant at the 1% significance level and rejects the original hypothesis, so the random effects model is selected; when comparing the random effect model is compared with the fixed effect model, the bootstrap-based Hausman test, which is not significant and accepts the original hypothesis, so the random effect model can be chosen. In summary, the random effect model should be selected for the study.

Benchmark model regression results

As a result of economic development, there are obvious differences in population aging, industrial structure upgrading and carbon emissions among Chinese provinces. Therefore, in order to further analyze the impact of regional differences in carbon emissions due to population aging, the text divides the country into three regions from the perspective of regional heterogeneity, namely, the east (economically developed regions), the central (economically sub-developed regions), and the west (economically underdeveloped regions). The impact of population aging on regional carbon emissions is discussed separately, the regression results as follows *Table 4*.

Table 4. *Benchmark model regression results*

Variable	National	East	Central	West
lnAG	-0.128***	0.101	-0.236***	-0.056***
lnUR	0.234***	0.002	0.186**	0.352***
lnGDP	0.468***	0.141*	0.225***	0.301***
lnOP	0.014	-0.112	0.135	0.012*
lnES	0.358***	0.255***	0.301***	0.235***
lnTI	-0.098***	-0.286***	-0.156***	-0.085***

*, **, and *** means $P < 0.1$, $P < 0.05$ and $P < 0.01$

In *Table 4,* from the national sample, the coefficient of population aging rate is -0.128, which indicates that the aging degree of a region's population will also have an impact on the total amount of CE, and for every percentage point increase in the aging rate, the total amount of CE in the region will be reduced by 0.128 tons. The inhibitory effect of population aging on CE is mainly reflected in two aspects, namely the production channel and the consumption channel. From the perspective of different regions, in the eastern region, population aging has no obvious negative impact on carbon emissions in the region, which may be due to the fact that in the cities with rapid economic development, the level of medical care, quality of life, and social services is relatively high, and the per capita life expectancy of the elderly population is extended, which deepens population aging in the eastern region, while further consuming more energy, and thus population aging in the eastern region has a positive effect on carbon emissions, but does not pass the significance test; in the central region, the siphoning effect of the eastern region, a large number of working-age population outflows, which deepens the degree of aging in the sub-developed regions, and the aging population has a lower demand for the use of energy substances in life and consumption, so it significantly reduces the carbon emissions. In the western region, population aging has a significant negative impact on

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carbon emissions in the region, probably because in the less developed regions, a large number of young people choose to go out to work, the degree of aging is deeper, and the aging population pays more attention to health, and has a higher acceptance of the use of clean energy, which inhibits the rise of carbon emissions in the region.

Threshold effect regression results

Threshold test

It is known through literature combing that population aging impact on CE may be linear or non-linear, i.e., when the degree of population aging exceeds a certain threshold, its effect on CE may be different. Therefore, this section tests the nonlinear relationship of the impact of population aging on CE through the threshold effect. The asymptotic value of the F-statistic is obtained by Bootstrap test, and the threshold is tested at 100 times of individual point search as well as 300 times of bootstrap sampling, respectively. In the case of population aging as both the independent variable and the threshold variable, the triple threshold test was conducted, and according to the results in *Table 5,* in the single-threshold test, its p-value is 0.002, which indicates that the single-threshold test result is significant. Therefore, there is a single threshold for the threshold effect of population aging on CE, and there is only a single threshold effect. According to *Table 6,* it can be known that the estimated value of the single threshold is -1.633, and since the variables are logarithmized before conducting the test, and the effect of population aging on CE will be different.

Table 5. *Threshold test results*

Explanatory variable	Threshold variable	Hypothesis testing	F-statistic	P value
lnAG	lnAG	Single threshold	33.467***	0.002
		Double threshold	2.34	0.148
		Triple threshold	5.89	0.762

Table 6. *Threshold estimation results*

Variable	Threshold variables	Threshold number	Estimated threshold
lnAG	lnAG	0.000	-1.633

Threshold effect model estimation

In *Table 7,* population size, urbanization rate, energy consumption intensity all significantly affect CE, and the estimated direction of the model is consistent with the direction of the benchmark regression model. Secondly, when we look at the threshold variables, when the population aging as a threshold variable, when the degree of population aging is less than or equal to -1.633, population aging will significantly inhibit carbon dioxide emissions, and its coefficient is -0.248 at 1% level of significance, and when the degree of population aging is greater than -1.633, the aging of the population will likewise inhibit carbon dioxide emissions, and its coefficient is -0.498, and also pass the significant test, which proves that when population aging crosses the threshold, its inhibition of carbon dioxide emissions will be greater, and the effects of other variables do not change significantly.

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Table 7. *Estimation results of threshold effect model*

Variable	Coefficient of elasticity	P value
lnAG (lnAG ≤ -1.633)	-0.248	0.000
lnAG (lnAG > -1.633)	-0.498	0.000
lnUR	0.114	0.003
lnGDP	0.278	0.001
lnOP	0.034	0.116
lnES	-0.412	0.000
lnTI	-0.116	0.002

Mediating effect regression results

The test results of the path “population aging- energy consumption -CE” are shown in Model 1 and Model 2 (*Table 8*). Interpretation of the same as above, with model 1, population aging on energy consumption coefficient of 0.144, and passed the 1% significance test, proving that the coefficient of a significant not 0. Population ageing is partly a result of socio-economic development, which requires natural resource inputs, and as social production expands further, more energy will be put to use, which means higher energy consumption. As the age of the elderly population grows, after retirement, the time spent outside the home will be greatly reduced, in the home time, household appliances, kitchen natural gas and other household energy will be used more. Over time, the number of older people in our country is increasing year on year, which will lead to an increase in our household energy consumption, and in turn, an increase in CE.

In model 2, energy consumption can significantly promote CE, and its impact coefficient is -0.428, proving that the coefficient b is not 0, indicating that the ab product is not 0, that is, there is a mediating effect. In *Table 8,* the level of aging still has a significant positive effect on per capita domestic energy consumption, with an increase of 0.144 kg of standard coal per capita for every 1 percentage point increase in the share of the elderly population. This finding is consistent with studies in the U.S. and Japan (O’Neill and Chen, 2002; Yamasaki and Tominaga, 1997), and one possible explanation is that older people spend more time at home on average, and therefore consume relatively more domestic energy, such as water, electricity, coal, and natural gas, which contributes to the increase in CE in China. Overall, population aging may increase CE by consuming energy and thus increasing CE. The deepening of population ageing has led to a significant increase in the consumption of domestic energy for household use, thus further increasing the level of CE.

Table 8. *Intermediation effect regression results*

Variable	Model 1 LnES	Model 2 lnCI
lnAG	0.144***	-0.168***
lnUR	0.027***	0.167***
lnGDP	0.145**	0.239***
lnOP	0.256*	0.056
lnES		-0.428***
lnTI	0.118***	-0.159***

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Discussion

This chapter explores the mechanism of population ageing on carbon dioxide emissions and examines the pathways of population ageing on carbon dioxide by constructing a mediated effects model. It is argued that population aging can affect carbon emissions by influencing energy consumption. First, population aging suppresses carbon emissions, which is consistent with the conclusions of some scholars (Dalton et al., 2008; Hassan and Salim, 2015), but also with the existence of opposite conclusions of some scholars (Liddle and Lung, 2010; Menz and Welsch, 2012). Possible reasons for this are that from the national level, in the early stage of aging when the population size is in explosive growth, the aging caused by longer life expectancy does not result in a reduction of labor force, and the working-age population in this stage increases at a faster rate than the increase in the elderly population, and due to the existence of the demographic dividend, the economic development can still rely on the development of labor-intensive industries, and in the early stage of aging, the consumption structure matching the production structure also tends to be more energy-intensive and higher-value-added. In the early stage of aging, the consumption structure that matches the production structure also tends to be high in energy consumption and carbon emission, so whether it is from the production channel or the consumption channel, aging at the early stage will cause an increase in carbon emission. However, with the gradual deepening of the degree of aging, under the premise of the basic stability of the population size, the aging resulting from the prolongation of life expectancy will lead to the reduction of the working-age population, and then due to the disappearance of the demographic dividend, the economic development cannot continue to rely on the crude labor-intensive industries, and the industrial structure will shift to low-carbon capital-intensive and technology-intensive industries, and due to the increase in the number of elderly people, the overall social consumption preference will begin to change, and the consumption structure will gradually become more and more carbon intensive. Moreover, due to the increase of the elderly population, the overall consumption preference of the society will start to change, and the consumption structure will gradually become low-carbon and energy-saving. Therefore, from a comprehensive point of view, the impact of aging on carbon emissions has an inhibitory effect, which is consistent with the threshold effect of this paper, and the inhibitory effect will be strengthened after passing the inflection point, and the research in this paper further illustrates the stage of population aging in China. Secondly, population aging may increase carbon emissions by promoting energy consumption, which is consistent with the findings of Yamasaki and Tominaga (1997), probably because older people spend more time at home, which significantly increases per capita living energy consumption, and the increase in energy consumption has a negative impact on carbon emissions.

Conclusions and recommendations

Conclusion

The work takes 30 regions of China and selects the time period of 2008-2023. This paper analyzes in depth the mechanism of population aging impact on CE, explores whether the relationship between population aging and CE is nonlinear based on the

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threshold effect model, and further clarifies the inflection point value of the nonlinear relationship, and draws the conclusions as follows:

(1) The elasticity coefficient of the population aging rate is -0.128, which confirms that the degree of population aging also affects the total amount of CE, and for every percentage point increase in the aging rate, the total amount of CE in the region will be reduced by 0.128 tons. The inhibitory effect of population aging on CE is reflected in production channel and consumption channel.

(2) There is a non-linear relationship in the effect of population aging on CE, confirming the existence of a single threshold, the estimated value of which is -1.633. When population aging is greater than -1.633, population aging will also inhibit carbon dioxide emissions, and when its coefficient reaches -0.498, which is also significant at the 1% level, it proves that, when the degree of population aging crosses the threshold, the degree of its inhibition of carbon dioxide emissions will be greater.

(3) Population ageing is likely to increase CE by boosting energy consumption, with older people spending more time at home on average, and thus consuming relatively more domestic energy, such as water, electricity, coal and natural gas, stimulating increased levels of CE.

Recommendations

Strengthen the coordination and synergy of industrial, energy use, fiscal and taxation, financial and other policies, and give full play to the prying and guiding effect of financial funds. Increase financial expenditures for low-carbon transformation, increase R&D subsidies for energy-saving and carbon-reducing technologies, resource recycling technologies, and environmental protection technologies, and encourage enterprises to accelerate technological innovation and application of low-carbon technologies; support the corresponding tax policies, carbon accounting system, accelerate the construction of carbon market, and improve the supporting mechanisms for industrial restructuring and transformation; establish transformation funds, transformation financial subsidy mechanisms, etc., to promote the green and low-carbon development of high-carbon industries.

Accelerate the transformation and upgrading of industrial structure and the low-carbon transformation process of enterprises. Promote the transformation and upgrading of enterprises by increasing the government’s policy preferences, financial support and other initiatives, improve the infrastructure facilities required for the transformation and upgrading of enterprises, further enhance the allocation efficiency of factor resources, promote the rational layout of regional industries, encourage enterprises to increase investment in research, and the transformation of the environmentally friendly and low-carbon industries from high-pollution to low-pollution to promote industrial structure upgrading and promote the regional CE reduction. Actively respond to the development trend of aging, and formulate energy-saving and low-carbon policies from the perspective of population development. Research shows that economic factors are still the main factors affecting CE, but population aging has a significant impact on CE, which indicates that CE reduction policies should not only start from the economic and energy aspects, but also pay attention to the impact of demographic factors on CE, change people’s consumption patterns and consumption concepts, raise low-carbon awareness, advocate green consumption and low-carbon life, promote the harmonization of demographic changes and low-carbon development, and realize energy-saving and low-carbon policies from a demographic development perspective while coping with the problem of aging as early as possible. We will also promote the coordination of demographic changes and low-carbon development, and realize the development goals of carbon peaking and carbon neutrality in China as early as possible while coping with the problem of aging.

Improve the welfare system and enhance social security. Population aging not only reduces the labor force needed for economic development, but also increases the burden of social support, which is one of the challenges facing China’s development at present. However, population aging is a double-edged sword. Continuous aging will reduce the speed of economic development by reducing the “demographic dividend” and force the optimization and upgrading of industrial structure. The increase in the proportion of tertiary industry is conducive to the reduction of CE, which in turn improves the ecological environment.

Strengthening the construction of public service facilities to reduce the length of time the elderly spend at home. As China’s old-age dependency ratio continues to rise, the increase in the number of retired and elderly people has led to a prolongation of their home time, which in turn has led to a rise in the amount of energy consumed for home life. In this context, optimizing community shared infrastructure and guiding the elderly to transfer part of their home time to public places can effectively reduce the amount of energy used for home life. For example, the needs of community residents for cooling in summer and heating in winter can be met through public facilities. Carry out energy saving and emission reduction publicity campaigns targeting the elderly population. The expanding size of the elderly population makes their influence in energy consumption not to be ignored. Energy conservation and emission reduction publicity can be increased in the community, public transportation venues and television media, with energy-saving public service advertisements placed to teach the elderly more efficient and safer ways to save energy.

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