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Original Research

Moving Toward Carbon Neutrality in China: The Role of Human Capital in Reducing Carbon Intensity

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Abstract

With the looming global warming crisis, the question of how to achieve carbon neutrality is becoming an important issue confronting many countries. In this study, we use modern economic growth theory to investigate the impact of education on carbon intensity in China's 30 provinces from 2000 to 2021. On this basis, a fixed effect model, threshold model, and spatial Durbin model are used to analyze the influence mechanism and spatial effect. The results show that education significantly reduces carbon intensity; improving education reduces carbon intensity by upgrading industrial structure, enhancing green technology innovation, and upgrading consumption structure; the carbon intensity reduction effect of education is nonlinear and gradually increases with increasing levels of industrial structure upgrading, accelerating green technology innovation, and upgrading consumption structure; and education reduces carbon intensity mainly through the spillover effect. The negative spillover effects in provinces with low levels of carbon intensity are significantly greater than the direct effects, whereas the spillover effects in provinces with high levels of carbon intensity are negative but not significant.

Keywords: human capital, carbon intensity, intermediary effect, threshold effect, spillover effect

Introduction

Global economic growth, rapid industrialization, and a sharp increase in energy consumption have contributed to the enormous increase in greenhouse gas emissions and spurred climate vulnerabilities [1]. Climate change has hampered global socioeconomic and ecological environmental stability and thus has emerged as the greatest risk to humanity in the 21st century [2]. Therefore, there is now a consensus among major economies worldwide on how to achieve carbon neutrality. Although the world economy will have to rely on natural resources (e.g., oil and gas) for energy production in the foreseeable future, governments and researchers worldwide have made efforts to achieve net zero emissions and limit ecological issues. Proper solutions have become highly relevant for implementing the Paris Agreement and the 2030 global agenda.

A recent report by the CREA reveals that China is the world's largest emitter of greenhouse gases and the main source of growth in global carbon emissions over the past two decades. Against this background,

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the Chinese government has proposed a series of low-carbon strategies (e.g., the 2030 carbon peak and 2060 carbon neutrality) in the past decade [3]. Although some progress has been made, the carbon intensity (CI) in developing countries is much greater than that in developed countries [4]. Hence, carbon intensity reduction has become one of the most prevalent topics and a growing concern for stakeholders, governments, and scholars. Moreover, an increasing number of studies have explored carbon intensity reduction solutions. However, these studies often focus on the impacts of industrial structure, energy consumption, digital economy, and institutional design on CI [3-6].

Notably, human activities are the dominant factors that induce global carbon emissions. The Sustainable Development Goals (SDGs) have recognized that education-based human capital (HC) is important for the sustainable development of a nation [7]. In recent years, the relationship between HC and CI has progressively emerged as a prominent topic in the field of environmental protection. Researchers have proven that HC could be important in reducing carbon intensity by enhancing energy utilization efficiency and optimizing the energy structure [8, 9]. Moreover, educated individuals prefer to adopt pollution-free technologies, pay carbon taxes, and adhere to environmental norms in industries, transport, and households. Thus, it is important to further explore the role of HC in reducing CI in highly polluted areas such as China.

Some research gaps remain in this field of inquiry. First, despite its importance, the effect of HC on CI is controversial in various countries. HC is a two-edged sword that can promote environmental sustainability [8, 9] or damage [10, 11]. Notably, China, as the largest contributor to emissions, is pivotal in world mitigation. Thus, it is necessary to estimate the effect of HC on CI in China. Second, existing studies are limited to verifying relationships [8-11], and the influence mechanism has not been described systematically; for example, there is a gap in empirical studies that can verify the transmission mechanism and threshold effect. Finally, most of the empirical literature does not discuss the spillover effect of HC on CI, which may lead to inaccurate results [8-11]. Spatial economics theory suggests that educated individuals will migrate between provinces, which impacts the CI of local and surrounding areas [12]. With increasing regional integration, the spillover effects of HC and CIs have gradually increased.

To fill this gap, we address the following questions: Does HC affect CI, and if so, by what mechanisms? How does HC exert direct and spillover effects among neighboring regions? Is there any difference in such impacts at different CI levels? To rigorously confirm these issues, based on modern economic growth theory [13], we investigate the impacts of HC on CI for China's 30 provinces from 2000 to 2021. Furthermore, we estimate the transmission mechanism and threshold effect of HC's influence on the CI via the intermediary effect model and threshold model, respectively. Finally, we analyze the spillover effect of HC on CI. The heterogeneous effects of the CI are then further examined via the spatial Durbin model (SDM). This study not only provides a more thorough understanding of the contribution and influence mechanism of HC on CI but also helps policymakers in countries worldwide develop carbon reduction policies to achieve a net-zero future and mitigate global warming.

In contrast to the literature, this study makes three contributions. First, we integrate modern economic growth theory into the SDG framework, testing the potential power of education for macro analyses of sustainability. The findings shift the paradigm of climate policy evaluation toward dimensions of social welfare in China. Second, carbon reduction commitments by businesses and individuals match carbon neutrality initiatives. Thus, we are not limited to verifying relationships and further revealing the mechanism of HC's influence on CI from the above perspectives – industrial structure upgrading (ISU), green technology innovation (GTI), and consumption structure upgrading (CSU) – which empirically informs the design of carbon neutrality targets and deepens the existing research. Finally, we estimate the spillover effect of HC on the CI, followed by a heterogeneous test of the CI based on the SDM. These interesting results expand upon previous static research and have practical significance for guiding the flow of talent and carrying out regional synergistic development tailored to local conditions.

The rest of the paper is organized as follows: section 2 introduces the literature review.

Section 3 describes the material and methods; section 4 reports the empirical results and draws the discussion; section 5 presents the conclusions.

Literature Review

Maintaining economic growth while reducing carbon emissions (CE) is challenging because CE is associated with human economic activities [5, 6]. As research continues, modern economic growth theory affirms that HC is important for attaining the decarbonization of the economy and a country's sustainable development [13]. Thus, based on this theory, many empirical studies validate how education-based human capital can be associated with environmental degradation from different perspectives. Due to differences in methods, sample data, and study periods, three distinct categories of results are obtained.

Some researchers have suggested that HC mitigates CO_2 emissions in OECD economies [9], in G7 countries [14], in China [15, 16], and in 163 countries [17]. A positive role of HC in reducing CI is also found in China [18]. Similar findings have been reported by Zafar et al. [19], Zafar et al. [20], and Ahmed et al. [21], who assess the USA, OECD economies, and China and show that education reduces the ecological footprint. Another study by Zafar et al. [22] for Asia-Pacific Economic

Cooperation countries reveals that education reduces emission levels. Similarly, Zafar et al. [23] and Zaman et al. [24] suggest a negative relationship between education and emissions for top remittance-receiving countries and China, respectively.

Conversely, numerous studies have shown that HC positively impacts CE [10, 11] or expands the ecological footprint in Pakistan [25]. Other studies also reveal a significantly positive association between education and emissions for high-HDI countries [26, 27], BRICS countries [28], and China [29]. Similarly, Zhang et al. [30], for Indonesia and Sub-Saharan Africa, find that education expenditures contribute to deteriorating environmental quality. Similar findings have been reported by Ahmed et al. [31], who find that education adds to CO_2 emissions for Latin American and Caribbean countries.

Studies have revealed that the effects of HC on CE exhibit time-stage heterogeneity [32, 33], educational stage heterogeneity [34], and regional or national heterogeneity. However, the results are inconsistent regarding this effect in emerging economies in low-income countries [35]. Additionally, researchers argue that the effect of HC on CI shows an inverted N-shaped [36] or inverted U-shaped pattern [37].

In summary, the literature shows that HC is a two-edged sword that can promote environmental sustainability or damage. However, there are still several research gaps. HC is included in analyses of how socioeconomic factors impact CI but is usually treated as a control variable. More importantly, the influence of HCs on CI has failed to reach a consensus globally, necessitating further inquiries. The impact mechanism and threshold effect have also rarely been empirically studied. Furthermore, despite the development of spatial econometrics, related research fails to estimate the spillover effect of HC on CI. Thus, to fill these gaps, we first investigated the impacts of HC on CI for China's 30 provinces. We estimated the transmission mechanism and threshold effect, followed by the spillover effect of HC on CI.

Material and Methods

Variables

Dependent Variable

The dependent variable is CI. The CI is calculated by the regional total CO_2 emissions/regional GDP per capita, which is an effective indicator for countries worldwide to measure the balanced development of economic and ecological environmental protection [3]. Compared with total carbon emissions or per capita carbon emissions, it has proven to be more practical as a measure of energy intensity and as a guide for allocating responsibility for reducing emissions [1]. The data come from the MEIC database, which uses the emission factor method to calculate carbon emissions based on subsectoral energy consumption.

Independent Variables

The independent variable is HC, calculated by the aggregate number of years of education per capita, which refers to the accumulation of knowledge and skills acquired through investment in education by the labor force. The formula is set as follows:

$$HC_{it} = \sum_{i=1}^{n} p_i y_i \left(p_i = 6,9,12,15,16,19 \right) \Big/ P_{it} \tag{1}$$

where the educational coefficient p_i is obtained by assigning weights to 6 different types of educational levels (primary school degree, junior school degree, high school degree, college degree, bachelor's degree, and postgraduate degree) of 6, 9, 12, 15, 16, and 19, respectively, based on years of education. Then, p_i is multiplied by y_i, the proportion of the labor force with different educational levels. Finally, $p_i y_i$ is divided by P_{it}, the total population aged 6 and over [38].

Mediating and Threshold Variables

(1) ISU: The "structural effect" of the environmental Kuznets hypothesis (EKC) states that when the dominant sector of the economy shifts from capital-intensive industries to technology-intensive industries, an advanced industrial structure greatly reduces the reliance on energy inputs. ISU is represented by the ratio of the tertiary industry's output value to the secondary industry's output value. This measure can reflect the service orientation of the economic structure [39].

(2) GTI. Green technology refers to a combination of emission-reduction technology, energy-efficiency technology, and renewable energy technology. Stronger green technology innovation capabilities are conducive to expanding the use of renewable energy and decreasing energy consumption and carbon emissions per unit of output value in production [40]. The number of green invention patents granted represents GTI.

(3) CSU: In the process of upgrading the consumption structure, educated consumers pay more attention to enjoyment and development consumption, and this type of consumption helps to transform resource and environmental utilization patterns and promote green economic development [41]. The formula is set as follows:

$$CSU_t = \sum_{i=1}^{2} \frac{P_{it}}{P_t} \left(\frac{Jun_{it}}{C_{it}} + \frac{Int_{it}}{C_{it}} \times 2 + \frac{Sen_{it}}{C_{it}} \times 3 \right) \tag{2}$$

where Jun_{it}, Int_{it}, and Sen_{it} represent primary consumption, intermediate consumption, and senior consumption, respectively. Primary, intermediate, and senior consumption weights are 1/6, 2/6, and 3/6, respectively; C_{it} and P_{it} represent the total consumption and total population in rural and urban areas at time t, respectively; and i is used to distinguish urban and rural areas. P_t represents the total population in rural and urban areas at time t.

Control Variables

According to the STIRPAT model [42], CIs are affected by many factors, such as population, affluence, and technology. Thus, we adopt the following control variables [17, 19, 26, 30]: foreign direct investment (FDI), financial development (FD), population structure (Pop), economic development (Eco), and information and communication technology (ICT) (Table 1).

Sample and Data Sources

We select 30 provinces in China from 2000 to 2021 as samples for the empirical analysis. These data sources include the China Statistical Yearbook and the China Population and Employment Statistics Yearbook. The CI data come from the MEIC model network. All research data are estimated at the 2000 price level and are in logarithmic form. All the VIFs are lower than the critical value of 10, indicating no multicollinearity problems. Table 2 displays the descriptive statistics of the variables.

Method

Baseline Model

We explore the nexuses among the HC and CI by a regression on the population, affluence, and technology (STIRPAT) framework credited to Dietz and Rosa [42]. Some empirical studies have confirmed that the STIRPAT is an efficient framework for modeling the determinants of CI [1, 3]. The framework can be specified as follows:

$$I_{it} = \alpha_0 + \rho_1 P_{it} + \rho_2 A_{it} + \rho_3 T_{it} + u_i + v_t + \varepsilon_{it} \quad (3)$$

where I denotes environmental pollutants and P, A, and T denote population, affluence, and technology, respectively. Here, i represents one investigated province, t represents one research year, α_0 is a constant, and ρ_1, ρ_2, and ρ_3 are estimated coefficients. u_i represents the individual fixed effect, v_t represents the time fixed effect, and ε_{it} is a random error term.

Table 1. Control variable selection and symbols.

Variable	Definition	Symbol
Foreign direct investment	Amount of foreign direct investment/provincial GDP	FDI
Financial development	(Deposits and loans)/provincial GDP	FD
Population structure	(Population between 0-14 years old + over 65 years old)/(Population between 15-64 years old)	Pop
Economic development	Provincial GDP per capita	Eco
Information and communication technology	Total postal and telecommunications business volume/provincial GDP	ICT

Table 2. Descriptive statistics.

Variable	Obs	Mean	Std. dev.	Min	Max
lnCI	660	-8.552	0.678	-10.722	-6.955
lnHC	660	2.151	0.131	1.693	2.548
lnISU	660	1.734	0.829	0.195	4.841
lnGTI	660	4.822	1.926	0.000	9.114
lnCSU	660	0.040	0.093	-0.279	0.274
lnFDI	660	0.607	0.473	-0.623	1.856
lnFD	660	-2.960	0.573	-4.244	-1.239
lnPop	660	1.040	0.324	0.346	2.025
lnEco	660	9.185	0.522	7.887	10.781
lnICT	660	-4.196	1.121	-9.688	-1.921

Based on the literature [3, 4], we further expand the model to construct Equation (4), which tests the effects of HC on CI. This can be expressed as:

$$\ln CI_{it} = \alpha_0 + \alpha_1 \ln HC_{it} + \alpha_2 \ln FDI_{it} + \alpha_3 \ln FD_{it} + \alpha_4 \ln Pop_{it} + \alpha_5 \ln Eco_{it} + \alpha_6 \ln ICT_{it} + u_i + v_t + \varepsilon_{it} \quad (4)$$

Intermediary Effect Model

We further construct intermediary effect models to estimate such transmission channels (e.g., ISU, GTI, and CSU) to explore the transmission mechanism through which HC affects CI. Based on Equation (4), the intermediary effect model is set as:

$$\ln CI_{it} = \alpha_0 + \alpha_1 \ln HC_{it} + \alpha_2 \ln Control_{it} + u_i + v_t + \varepsilon_{it} \quad (5)$$

$$lnMed_{it} = \beta_0 + \beta_1 lnHC_{it} + \beta_2 lnControl_{it} + u_i + v_t + \varepsilon_{it} \quad (6)$$

$$lnCI_{it} = \gamma_0 + \gamma_1 lnHC_{it} + \gamma_2 lnMedia_{it} + \gamma_3 lnControl_{it} + u_i + v_t + \varepsilon_{it} \quad (7)$$

where Med represents the intermediate variables (ISU, GTI, and CSU). Control represents all control variables (e.g., FDI, FD, Pop, Eco, and ICT). The other variables are set as before. If α_1 in Equation (5) is remarkable and both β_1 in Equation (6) and γ_2 in Equation (7) are remarkable, the intermediary effect is valid [43].

Threshold Model

The econometric model above has difficulty describing the nonlinear nexus between HC and CI. The threshold model is further employed to determine whether the effect of HC on the CI would change with the difference in threshold variables; this model accurately estimates the significance and value of the threshold variable, thus avoiding errors resulting from subjective judgment [44]. The single threshold model is as follows:

$$lnCI_{it} = \beta_1 lnthr_{it} \times I(q_{it} \le \gamma) + \beta_2 lnthr_{it} \times I(q_{it} \ge \gamma) + \beta_3 \ln HC_{it} + \beta_4 lnControl_{it} + u_i + v_t + \varepsilon_{it} \quad (8)$$

where I is the indicator function and γ is the threshold value (ISU, GTI, and CSU). The multi-threshold model (e.g., double threshold) is shown below. If the two threshold values are $\gamma_1 < \gamma_2$, then:

$$lnCI_{it} = \beta_1 lnGTI_{it} \times I(q_{it} \le \gamma_1) + \beta_2 lnGTI_{it} \times I(\gamma_1 < q_{it} \le \gamma_2) + \beta_3 lnGTI_{it} \times I(q_{it} > \gamma_2) + \beta_4 lnHC_{it} + \beta_5 lnControl_{it} + u_i + v_t + \varepsilon_{it} \quad (9)$$

Spatial Econometric Model

Researchers have shown that HC and CI may be spatially dependent [38]. The regression results of the basic model may lead to biased estimation results [12]. Thus, further exploration of the spillover effects between HC and CI through a spatial econometric model is essential. First, the global Moran's I index tests the spatial correlation between HC and the CI. This is calculated as follows:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(X_i - \overline{X})(X_j - \overline{X})}{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij} \sum_{i=1}^{n}(X_i - \overline{X})^2} \quad (10)$$

where X_i denotes the observed value of province i, i.e., the HC and CI; n is 30; and W_{ij} denotes the geographic distance spatial weight matrix. The range of Moran's I is [-1, 1]. A Moran's I value close to -1 or 1 indicates that the level of global spatial autocorrelation is high [12].

In Equation (10), W_{ij} is expressed as follows:

$$W_{ij} = \begin{cases} \frac{1}{d_{ij}^2}, i \ne j \\ 0, i = j \end{cases} \quad (11)$$

where d_{ij} denotes the geographic distance between the provincial capital cities of province i and province j. If province i is closer to province j, W_{ij} will increase.

The SDM is subsequently used to explore the spillover effects of HC on the CI. Based on Equation (4), the SDM is defined as:

$$lnCI_{it} = \rho\sum_{j=1}^{n} W_{ij} lnCI_{it} + \beta_1 lnHC_{it} + \beta_2 lnControl_{it} + \sum_{j=1}^{n}\theta_1 W_{ij} lnHC_{it} + \sum_{j=1}^{n}\theta_2 W_{ij} lnControl_{it} + u_i + v_t + \varepsilon_{it} \quad (12)$$

where ρ and θ denote the spatial lagging coefficients of variables; β denotes the regression coefficients of variables; and the remaining variables are set as above [12].

Results and Discussion

Basic Regression

To better conduct the empirical analysis, model selection is performed. According to the Hausman test, the result is 0.000, so the OLS with a fixed effect model is selected. Furthermore, the result of the F test is 0.000, so the OLS with double fixed effects (FE) is suitable for analysis. Thus, we select the FE model to estimate the impact of HC on the CI, as shown in Table 3.

Column (2) shows that the significant coefficient of HC is -0.825, indicating that improvements in HC will reduce CI in China and help environmental well-being. This is plausible because HC can directly reduce CI through green support and capital investment [8, 9]. On the one hand, education is a useful tool for bringing about awareness of the spending pattern of economic agents, which can potentially awaken individuals' environmental consciousness, enabling them to realize the significance of sustainability and actively participate

Table 3. Results of baseline regression.

Variable	(1)	(2)
	Random effects	Fixed effects
lnHC	-2.520*** (0.244)	-0.825*** (0.296)
lnFDI	0.001 (0.014)	-0.039*** (0.011)
lnFD	-0.447*** (0.073)	0.295*** (0.077)
lnPop	-0.023 (0.058)	-0.248*** (0.053)
lnEco	-0.661*** (0.074)	-0.468*** (0.076)
lnICT	-0.005 (0.016)	0.148*** (0.044)
Time effect	NO	YES
Individual effect	NO	YES
Hausman test	-	62.62 [0.000]
F test	-	21.55 [0.000]
Obs	660	660
R^2	0.793	0.882

**p*<10%, ***p*<5%, ****p*<1%

in carbon intensity reduction. For example, education has consistently increased environmental concern, willingness to pay for environmental protection, and support for environmental policy and products. On the other hand, education is a main supplier of the green workforce, effectively providing sufficient and high-quality human capital for green production to promote the green optimization of socioeconomic activities. Therefore, improving HC acts as a catalyst for sustainable development goals and reduces the reliance on replenishing natural resources.

These findings contribute to the debate on the impact of HC on environmental variables. Unlike most studies that explore the role of industrial structure, energy consumption, and technological innovation in reducing CI [3-6], we form a link between HC and sustainable development, emphasizing the positive role of HC as an independent variable in carbon intensity reduction. The conclusions provide support for researchers who hold a "positive" view that HC reduces CI [8, 9] and provide confidence to researchers who hold a "negative" view that HCs increase CE [10, 11], possibly because HC in those studies cover quantity dimensions rather than quality dimensions. Thus, in the long run, there is strong evidence to conclude that the HC is a panacea for decarbonizing the economy beyond merely training in China, further extending the HC framework proposed by modern economic growth. Moreover, China possesses great potential for human capital development since it ranked 43rd of 122 countries in terms of the 2020 human capital index and became an aging society in 2000. These findings also affirm the guidelines of the Paris Agreement 2017, which states that education is a central priority for every country and should be improved to solve environmental problems [7]. However, for many developing economies where education remains the least prioritized subject, these results might also persuade the government to invest more in education that promotes both environmentally and economically sound growth.

The results also reveal that FDI, Pop, and Eco positively impact the reduction in the CI. The advanced technology and better management practices introduced by FDI could improve industry efficiency in China and decrease CI. This finding indicates that the technical effect of openness is greater than the structural effect, providing evidence for the pollution halo hypothesis [19], where consumers with higher per capita income demand consume more green products (e.g., low-energy-intensity household appliances). Therefore, this result also reveals that the Chinese economy is moving toward low-carbon development, which provides further evidence for the EKC [17]. Additionally, with the increase in the number of children under 15 years of age and elderly people, the energy consumption scale and consumption levels are decreasing [30], and the consumption tendency is gradually focused on the medical technology industry and consumer service sectors, decreasing the share of energy-dependent industries and thus curbing the growth of CI.

However, FD and ICT are responsible for higher CIs. FD generated human demand, and the financial sector distributed funds to businesses, stimulating manufacturing processes and increasing industrial contamination and waste. These findings are consistent with those of Iqbal and Kalim [27]. The application of ICT and the adoption of ICT-based devices may have expanded the scale of energy demand, leading to a decrease in environmental quality. Previous research supports these findings [26].

Robustness Test

Substitution of the Dependent Variable

In addition to the CI, researchers have often adopted per capita carbon emissions (CEs) to measure the carbon emission level of each area [6]. Therefore, the regression analysis was performed again in this study by applying CE as the dependent variable. The results are presented in Column (1) of Table 4, which shows that utilizing the new dependent variable accounting method did not alter the baseline regression results.

IV-2SLS

To eliminate endogeneity resulting from omitted variables and/or reverse causality, we employ the common approach of two-stage least squares (2SLS) and identify instrumental variables (IVs) to address this issue. Furthermore, following existing research [45], the lagged value of the independent variable in each province is adopted as an IV. The first-stage F value for the IVs is 133.72, indicating no weak instrumental variable problem. These IVs satisfy the relevance condition and exclusion conditions simultaneously. The results in Column (3) of Table 4 exhibit no noteworthy difference from our baseline results, suggesting the robustness of our findings.

Intermediary Effects Analysis

We further explore the transmission mechanisms through which HC affects CI via the intermediary effect model for more policy insights from ISU, GTI, and CSU perspectives. The results are shown in Table 5.

First, Column (2) illustrates that HC had a significant positive relationship with ISU (1.106). Column (3) shows that the regression coefficients of HC and ISU on the CI were -0.730 and -0.085, respectively. Our findings show that ISU has a mediating effect on CI. Thus, the fact that HC reduces CI by promoting industrial structure upgrading holds true. This finding shows that HC is a main component of industrial transformation. On the demand side, higher educational attainment positively affects environmental quality, as more educated consumers demand more green products and are more likely to push firms to reduce pollution levels, thus promoting tertiary industry development. On the production side, the increased input of HC can reduce energy input due to the strong substitution relationship between HC and energy. Thus, driven by HC, the industrial structure shifts from being pollution-intensive to being environmentally friendly, which can promote CI reduction.

Table 4. Results of robustness tests.

Variable	(1)	(2)	(3)
	lnCE	lnCI	lnCI
lnHC	-0.366* (0.227)	-	-1.421*** (0.321)
lnHC$_{t-1}$	-	0.472*** (0.036)	-
lnFDI	-0.006 (0.013)	-0.002 (0.001)	-0.053** (0.022)
lnFD	0.254*** (0.068)	-0.006 (0.010)	-0.119 (0.090)
lnPop	-0.628*** (0.053)	-0.020*** (0.007)	0.322*** (0.067)
lnEco	1.066*** (0.072)	0.037*** (0.009)	-0.242*** (0.073)
lnICT	-0.017 (0.015)	0.009 (0.006)	-0.062* (0.036)
Time effect	YES	YES	YES
Individual effect	YES	YES	YES
F value	-	133.72 [0.000]	-
Obs	660	630	660
R^2	0.793	-	0.444

*p<10%, **p<5%, ***p<1%

Second, Column (4) shows that an increase in HC promotes green technology progress; HC increases by 1%, and green technology improves by 2.512%. The regression coefficients of HC and GTI in Column (5) are -0.718 and -0.042, respectively, suggesting that GTI has a mediating function; hence, an increase in HC promotes the occurrence, introduction, and absorption of green innovation. In addition, educated individuals' demand for green products will be stronger, indirectly pushing firms to accelerate GTI. Finally, the educated public can experience behaviors that damage the environment and are not conducive to carbon neutrality in a variety of ways, which can promote GTI. The ecological modernization theory also suggests that GTI is a cornerstone of climate change mitigation at the global scale, and the powerful productivity caused by GTI substantially accelerates the decarbonization of the economy. This conclusion also supports Kelly's results [40]. In this paper, we refine the mediation of GTI and more accurately grasp the impact mechanism of GTI.

Finally, Column (6) verifies the significant positive impact of HC on CSU (0.075), which shows that increasing HC can promote CSU. Column (7) illustrates that HC and CSU negatively impact CI. Clearly, CSU has a mediating function in the relationship between HC and CI. Specifically, the education level of individuals determines people's cognitive level of low-carbon development and consumption. Furthermore, education can upgrade consumption structure and increase consumption of less carbon-intensive goods and services, such as saving energy, recycling, saving water, and preferring eco-labeled food and appliances, thus reducing carbon intensity in the residential sector. Individual consumption behaviors have been shown to be an influential indirect force in emissions abatement. This finding supports the evidence that education has effectively improved individuals' awareness of environmental protection while empirically extending consumption structure upgrading as an important mechanism for the impact of HC on CI.

Based on researchers exploring the impact of HC on CI [8-11], we further validate HC's influence mechanism. The results of the mediation tests illustrate that moving toward sustainability requires strategies on the economic front as well as a sustainable lifestyle and awareness at the individual level. These observations are consistent with those of other studies [5, 6] but contradict other studies that confirm the rebound effect of innovation on environmental pollution [46]. In terms of their share, the mediating effects of ISU and GTI are greater than those of CSU. Thus, it is necessary to guide individuals to improve their green consumption

Table 5. Results of intermediary effects.

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	lnCI	lnISU	lnCI	lnGTI	lnCI	lnCSU	lnCI
lnHC	-0.825*** (0.296)	1.106** (0.484)	-0.730** (0.295)	2.512*** (0.660)	-0.718** (0.299)	0.075*** (0.050)	-0.757*** (0.291)
lnISU	-	-	-0.085*** (0.025)	-	-	-	-
lnGTI	-	-	-	-	-0.042*** (0.018)	-	-
lnCSU	-	-	-	-	-	-	-0.903*** (0.191)
lnFDI	-0.039*** (0.011)	-0.033* (0.018)	-0.042*** (0.011)	0.027 (0.025)	-0.038*** (0.011)	-0.004 (0.002)	-0.042*** (0.011)
lnFD	0.295*** (0.077)	0.109 (0.126)	0.304*** (0.077)	0.095 (0.172)	0.299*** (0.077)	-0.006 (0.016)	0.290*** (0.076)
lnPop	-0.248*** (0.053)	0.475*** (0.087)	-0.208*** (0.054)	0.654*** (0.119)	-0.221*** (0.054)	0.060*** (0.011)	-0.194*** (0.054)
lnEco	-0.468*** (0.076)	-0.736*** (0.124)	-0.531*** (0.077)	-0.197 (0.169)	-0.476*** (0.076)	0.007 (0.016)	-0.461*** (0.074)
lnICT	0.148*** (0.044)	0.253*** (0.073)	0.170*** (0.044)	-0.148 (0.099)	0.142*** (0.044)	-0.013 (0.009)	0.137*** (0.044)
Time effect	YES	YES	YES	YES	YES	YES	YES
Individual effect	YES	YES	YES	YES	YES	YES	YES
Obs	660	660	660	660	660	660	660
R^2	0.882	0.688	0.885	0.948	0.883	0.847	0.887

*p<10%, **p<5%, ***p<1%

awareness and practice low-carbon lifestyles through, for example, energy conservation, recycling, saving water, consumption of eco-labeled food, and the use of eco-labeled electric appliances, which cause the carbon reduction effect of upgrading the consumption structure to be ideal. The findings not only support ecological modernization theory and provide empirical evidence to illuminate the "black box" of their interaction but also offer specific paths for China to fulfill the carbon neutrality target by 2060.

Threshold Effects Analysis

Although HC reduces CI by enhancing ISU, GTI, and CSU, their nexus may have depended on the ISU, GTI, and CSU levels. We further construct a threshold model and explore the nonlinear relationship between HCs and CIs. Table 6 reports the estimated threshold values and their respective confidence intervals.

Furthermore, we estimate the threshold panel model, as shown in Table 7.

First, when the ISU is less than 1.737, the significant coefficient of HC is -1.486; when the ISU is greater than 1.737 and less than 3.498, the significant coefficient of HC is -1.564; and when the ISU is greater than 3.498, its inhibitory effect becomes stronger. This result indicates that industrial structure upgrades help increase the inhibitory effect of HC on CI. The reason is that when the industry structure increases to a certain level, more educated individuals engage in tertiary industry, represented by high-tech and new energy industries. The matching degree of the human capital structure and industrial structure reduces the CI of a country.

Second, when GTI is less than 5.518, a 1% increase in education may have caused a 1.084% decrease in CEI. When GTI is greater than 5.518 and less than 6.936, a 1% increase in education may have caused a -1.203% decrease in CEI. When the GTI is greater than 6.936, a 1% increase in education may have caused a -1.335% decrease in CEs. These findings indicate that the effects of education on emission reduction differ with varying levels of GTI. As the GTI increases, its impact gradually increases. A higher GTI makes it easier for businesses to adopt stricter environmental rules and for advanced low-carbon technologies to be matched with human capital, thereby reducing CI.

Finally, at a low level of consumption structure upgrades (lnco≤0.167), the significant regression coefficient is negative, i.e., -1.765, whereas at a high level (lncon>0.167), the regression coefficient becomes greater. This finding shows that with the improvement of the consumption structure, the inhibitory effect

Table 6. The significance test results for the threshold effects.

Variable	Threshold type	F value	P value	Critical values			Threshold estimation value	95% confidence interval
				10%	5%	1%		
lnISU	Single	124.720	0.000	47.807	57.138	70.460	1.737	[1.715, 1.750]
	Double	48.290	0.070	42.552	50.819	72.120	3.498	[3.413, 3.509]
							3.498	[3.413, 3.509]
lnGTI	Single	195.550	0.000	51.093	63.588	76.789	6.532	[6.521, 6.548]
	Double	123.550	0.000	40.155	52.332	67.804	6.936	[6.879, 6.943]
							5.518	[5.507, 5.526]
lnCSU	Single	111.770	0.000	60.995	68.882	82.982	0.167	[0.163, 0.169]

Table 7. Results of the threshold effects.

Variable	(1)	(2)	(3)
lnHC (lnind≤1.737)	-1.486*** (0.330)	-	-
lnHC (1.737 < lnind≤3.498)	-1.564*** (0.324)	-	-
lnHC (lnind>3.498)	-1.795*** (0.319)	-	-
lnHC (lnGTI≤5.518)	-	-1.084*** (0.321)	-
lnHC (5.518 < lnGTI≤6.936)	-	-1.203*** (0.320)	-
lnHC (lnGTI>6.936)	-	-1.335*** (0.324)	-
lnHC (lncos≤0.167)	-	-	-1.765*** (0.393)
lnHC (lncos>0.167)	-	-	-1.923*** (0.394)
F value	59.570	68.600	63.080
Obs	660	660	660
R^2	0.838	0.867	0.824

**p*<10%, ***p*<5%, ****p*<1%

of HC on CI increases. One possible explanation is that when the consumption structure of individuals reaches a certain level, educated individuals are more aware of sustainable development and practice low-carbon lifestyles, thereby reducing CI.

Spatial Effects Analysis

Spatial Autocorrelation test

Table 8 shows that all the global Moran's I values of HCs and CIs are significantly positive. The findings reveal that HCs and CIs are not completely random and have positive spatial autocorrelation, which is affected by geographic neighbors; provinces with low HCs and CIs are geographic neighbors, as are those with high HCs and CIs. Moreover, the global Moran's I values for EC and CI present an overall downward trend, which means that the spatial autocorrelation of the variables decreased.

Model Selection

According to the spatial autocorrelation test results, HC and CI exhibit spatial effects. Thus, the spatial econometric model is appropriate for this empirical investigation. Based on the conclusions of LeSage and Pace [47] and Elhorst [48], first, the Lagrange multiplier (LM) and robust LM tests indicate that there are spatial correlations and that the SDM is suitable. The likelihood ratio (LR) and Wald tests are then employed to test the SDM, which reveals that it could not be degraded

Table 8. Global Moran's I index of HC and CI.

Year	HC	CI	Year	HC	CI
2000	0.169***	0.099***	2011	0.133***	0.083***
2001	0.159***	0.097***	2012	0.145***	0.089***
2002	0.159***	0.093***	2013	0.155***	0.081***
2003	0.134 ***	0.083***	2014	0.145***	0.086***
2004	0.155***	0.083***	2015	0.127***	0.089***
2005	0.153***	0.084***	2016	0.132***	0.090***
2006	0.151***	0.071***	2017	0.120***	0.084***
2007	0.135***	0.073***	2018	0.123***	0.081***
2008	0.143***	0.082***	2019	0.128***	0.089***
2009	0.145***	0.081***	2020	0.115***	0.088***
2010	0.147***	0.087***	2021	0.119***	0.090***

*p<10%, **p<5%, ***p<1%

to the spatial error model (SEM) or the spatial lag model (SLM). Finally, Hausman and joint significance likelihood ratio (LR) tests are adopted to determine whether the SDM with double fixed effects is the most reasonable for regression. All the test results are shown in Table 9.

Regression Analysis

Based on spatial economics theory [12], an SDM with double fixed effects is built for the whole country. The regression results are presented in Table 10.

The results reveal the significant direct, spillover, and total effects of HC on CI, with regression coefficients of -1.031, -3.073, and -4.734, respectively, revealing that HC not only reduces CI in local provinces but also has negative spillover effects on neighboring provinces. Notably, the spillovers are larger than the direct effects, revealing that spillover effects are the main channel through which HC reduces the CI. The possible reasons are as follows: Spatial economics theory suggests that HC has spatial interconnections due to talent mobility and knowledge spillover [12]. With increasing regional integration, the spatial effect of HC on CI occurs through three channels. First, knowledge capital might move across neighboring provinces. For example, due to the pursuit of jobs or business activities, the mobility of educated individuals can accelerate knowledge spillover. Second, educated individuals may migrate across neighboring provinces (i.e., people study in one province but live in another). Third, educated individuals accept the concept of low-carbon development with both demonstration and peer effects, the education spillover that also strongly promotes the spread of environmental awareness and the upgrade in green production and consumption models across society.

Table 9. Test results of model selection.

Test	Statistics value
LM (err)	491.447***
Robust LM (err)	492.622***
LM (lag)	0.566
Robust LM (lag)	1.742
LR (err)	31.24***
LR (lag)	30.42***
Hausman test	-4.88
Wald test (err)	3.510**
Wald test (lag)	3.550**
LR (spatial fixed effects)	71.50***
LR (time fixed effects)	1074.68***

*p<10%, **p<5%, ***p<1%

This finding complements earlier studies [8-11]. The results also suggest that promoting targets for carbon emission reduction requires interregional and cross-regional collaboration, which can be realized with regional flows and education sharing and spatial interactions, positive externalities, and spatial linkages of emission reduction in terms of green awareness, production modes, and lifestyles. These findings broaden the application of spatial theory in education, economics, and environmental science and provide more possibilities for future research on the spatial spillover of HC and environmental variables.

Heterogeneity Test

Different levels of CI in provinces can result in disparities in the effect of HC on CI. Therefore, we sorted

Table 10. Results of the SDM.

Variable	Direct effect	Spillover effect	Total effect
lnHC	-1.031*** (0.295)	-3.703* (2.249)	-4.734** (2.317)
lnFDI	-0.041*** (0.0106)	-0.253*** (0.087)	-0.294*** (0.090)
lnFD	0.283*** (0.0698)	-0.389 (0.540)	-0.107 (0.546)
lnPop	-0.199*** (0.054)	-0.677** (0.343)	-0.876*** (0.331)
lnEco	-0.501*** (0.078)	0.628 (0.421)	0.127 (0.422)
lnICT	0.107** (0.0428)	0.895*** (0.267)	1.002*** (0.267)
ρ	-0.003 (0.152)	-0.003 (0.152)	-0.003 (0.152)
Time effect	YES	YES	YES
Spatial effect	YES	YES	YES
Obs	660	660	660
R^2	0.093	0.093	0.093
Log-L	314.653	314.653	314.653

*p<10%, **p<5%, ***p<1%

the 30 provinces from high to low based on the average annual CI from 2000 to 2021. The top 15 provinces were set as high-level CI areas, and the remaining 15 were set as low-level CI areas. The results are shown in Table 11.

Table 11 shows that the significant regression coefficients of the direct, spillover, and total effects of HC on the CI are -0.777, -4.127, and -4.904, respectively, revealing that HC significantly negatively impacted the CI in those provinces where the CI is low. The findings reveal that spatial spillover is the main channel for reducing education emissions in these provinces. While the direct effect of the significant regression coefficient of education on the CI is -0.667, the negative direct spillover and total effects are not significant when the CEI is high. The findings reveal that the spatial spillover advantages of education in emission reduction are not significant and that educated individuals do not fully function in the application and diffusion of the green production mode and consumption model.

Table 11. Results of the heterogeneity test.

Effect	Low-CI	High-CI
Direct effect	-0.777* (0.407)	-0.677* (0.376)
Spillover effect	-4.127* (2.161)	-0.206 (1.375)
Total effect	-4.904** (2.337)	-0.883 (1.439)
Control variables	YES	YES
ρ	0.125 (0.124)	-0.531*** (0.187)
Time effect	YES	YES
Spatial effect	YES	YES
Obs	330	330
R^2	0.404	0.073

**p*<10%, ***p*<5%, ****p*<1%

The possible reasons are as follows: Low-CI areas are mainly in developed regions (e.g., the east), characterized by a high proportion of tertiary industry. However, high-CI areas are mainly in developing regions (e.g., the central and western regions), where the economy has not entered the stage of sustainable development and there are lower levels of education stock. Moreover, educated individuals are usually associated with less green technology and more environmental pollution [8], so they cannot spread the ideas of environmental protection through demonstration effects. Furthermore, the pursuit of economic growth causes laborers to use more energy and produce more pollution, and the "rebound effect" greatly inhibits the role of HCs in reducing CI in neighboring areas. The findings can help policymakers develop regional development strategies more effectively by considering the spillover effects of HC.

Conclusions

We evaluate HC's influence by employing China's provincial data from 2000 to 2021 based on modern economic theory. Furthermore, we analyze the transmission mechanism and threshold effect of HC on CI. Finally, we examine the spillover effects of HC on the CI, followed by a heterogeneity test of the carbon intensity level.

The results reveal that (1) HC significantly reduces CI, which holds true for a series of robustness tests; (2) ISU, GTI, and CSU are the influential mechanisms by which HC reduces CI; (3) the carbon reduction effect of HC is nonlinear and gradually increases with increasing ISU, GTI, and CSU; and (4) HC reduces CI mainly through the spillover effect. The negative spillover effects in provinces with low CIs are significantly greater than the direct effects, whereas those in provinces with high CIs are negative but not significant.

Based on the above findings, we propose the following policy recommendations to help China achieve carbon neutrality.

First, the empirical analysis indicates that HC significantly reduces CI. Thus, investing more in HC is essential for increasing the human capital stock of a low-carbon economy. Local governments should establish multilevel input mechanisms from the government, individuals, and enterprises; increase the average years of education per capita; provide equitable access to education; improve school enrollment so that education is free for low-income and poor people; cultivate talent in low-carbon technology fields; promote environmental education; and add updated and wide content regarding climate issues to textbooks to further strengthen environmental protection knowledge and skill training for individuals such as climate change mitigation and adaptation policies, zero emissions technologies, carbon taxes, and carbon trading mechanisms.

Second, improving the HC reduces CI by ISU, GTI, and CSU, and the carbon reduction effect of HC gradually increases with the increase in ISU, GTI, and CSU. Thus, local governments should promote industrial structure upgrading, green technology innovation, and consumption structure upgrading. This specifically includes building a low-carbon energy system and industrial structure, increasing support for service industries and high-tech industries, promoting new energy industry development and accelerating the low-carbon transformation of the natural resource industry; building a market-oriented green technology system, encouraging enterprises to invest more in the research and promotion of green technologies, and carrying out green technology improvement actions in key industries and key products; guiding individuals to improve green awareness; implementing low-carbon consumption patterns, such as achieving a low-carbon diet, low-carbon residence and low-carbon travel; and giving full play to the role of low-carbon consumption behavior of individuals in carbon reduction [49, 50].

Finally, HC reduces CI mainly through the spillover effect. Thus, policymakers should consider the spillover effects of HC when adopting differentiated emission reduction policies according to local conditions. Provinces with low levels of CI have significant negative spillover effects, which should strengthen cooperation and exchange of education and improve the spillover and diffusion effects of HC, further promoting the spread of green environmental awareness and upgrading green production and consumption models. Moreover, provinces with high CI levels have negative but insignificant spillover effects; more attention should be paid to HC's impact on CI in the local province. Moreover, provinces with low CI levels should fully utilize the leading and overflowing functions, which drive provinces with high CI levels to build regional education resource clusters and green innovation environments, which can realize regional education linkages and promote regional integration and low-carbon development.

The findings have great theoretical and practical implications. At the theoretical level, the findings integrate modern economic growth theory into the SDG framework, testing the potential power of HC for macro analyses in sustainability. These findings also broaden the application of spatial theory in HC and provide more possibilities for future research on the spatial spillover of HC and environmental variables. At the practical level, the findings inform policymakers to develop carbon reduction policies and more effectively consider the impacts of HC and the spatial effects of neighboring regions, which can further promote investing more in HC. They also help policymakers in countries worldwide develop carbon reduction policies to achieve the Sustainable Development Goals 13, towards a net-zero future and mitigate global warming. In particular, our findings may provide useful suggestions for countries experiencing the transformation of economic development patterns (e.g., from traditional to sustainable growth).

There are some limitations that future studies can address. First, we consider the average years of education per capita as an HC indicator. Future research can measure HC using indicators such as tertiary education enrollment and education funding. Second, future analysis can explore the effect of the HC on the ecological footprint since CI only represents a small portion of complex environmental pollution issues that developing countries must address. Third, we select ISU, GTI, and CSU to explain the channels between HC and CI. Future research can explore other mechanisms, such as ICT and energy consumption structure. Finally, future research data can expand to more countries.

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Conflict of Interest

The authors declare no conflict of interest.

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