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RESEARCH ARTICLE

The impact of human capital on green economic efficiency: evidence from 280 prefectural cities in China

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Abstract
Balancing economic growth with resources and the environment to achieve sustainable development is a key issue in the development of all countries, and researchers are trying to find feasible development paths. The aim of this study is to examine the impact of human capital levels on green economic efficiency (GEE) and the underlying mechanisms in 280 prefecture-level cities in China and covering the 2003–2019 period. In addition, we calculate GEE including undesired outputs based on a super-efficiency slack-based measure (SBM) model, and we construct panel regression and moderating effect models for empirical studies. The results of the baseline regression study show that the improvement in the human capital level contributes to the GEE of prefecture-level cities. Among the control variables, the economic development level, foreign direct investment (FDI), city size, and the science and technology innovation (STI) level positively affect GEE, while industrialization and environmental regulation negatively affect GEE. The study results concerning the mechanism of action indicate that industrial structure upgrading plays a positive moderating role. That is, industrial structure upgrading can strengthen the effect of human capital on GEE, which is further clarified. This study suggests that government policies must favor the cultivation of high-level human capital, especially in the environmental protection industry, and that talent support strategies should be differentiated between regions to promote industrial structure upgrading and human capital matching through green technology development. Modern human capital theory reveals the important role of human capital in improving economic efficiency and provides new ideas for achieving sustainable development. This paper explores the role of human capital in improving the GEE based on the human capital perspective, which is important for research on the pathways to achieve sustainable development.

Keywords Human capital · Green economic efficiency (GEE) · SBM-DEA · Industrial structure upgrading · Moderating effect

Introduction

Global climate change is posing a growing threat to sustainable human development, and promoting a green economy is one of the critical elements of the new concept of sustainable development advocated by the United Nations. On the one hand, the carrying capacity of natural resources and the environment is limited. Additionally, not only is the economic development mode of mainly consuming natural capital is unsustainable, but it also easily causes high emissions and high pollution, thus increasing the burden on the environment. A green economy featuring low pollution, low energy consumption, and low emissions is a new way for countries to balance the economy and the environment. On the other hand, in the long run, developing a green economy can play a substantial and transformative role in achieving sustainable development (Borel and Turok 2013). After three decades of development, China's economic strength has increased significantly. The country has gradually entered a new normal characterized by medium to high speed, new dynamics, an excellent structure, and multiple challenges. However, the environmental problems brought about by rapid economic development in the past cannot be ignored. The Fifth Plenary Session of the 18th Communist

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Party of China (CPC) Central Committee set the five major development concepts of “innovation, coordination, green, openness and sharing” as the guidelines for China’s economic development, and it proposed for the first time the concept of green development to address the harmonious development of human beings and nature. The report of the 19th Party Congress points out that the new pattern of green development, a green lifestyle, and the balanced development of humans and nature should be promoted, and when deploying the modernized economic system, the report proposes to “insist on quality first and give priority to efficiency; and promote three major changes, namely quality, efficiency and power,” clearly indicating the importance of efficiency. Green economic efficiency (GEE) is an indicator used to evaluate the level of economic efficiency of a country or region based on the original economic efficiency, including the input of resource factors and environmental costs in the production process and it is a reflection of the level of green economic development (Guo et al. 2022). Therefore, developing a green economy and improving GEE hold great importance for the sustainable development of China’s economy.

Industrial policy is a type of policy that promotes efficiency and is a tool for governments to regulate the allocation of resources. It is widely used in countries around the world to promote sustainable economic development. With limited resources, a focused industrial policy is an important tool for the Chinese government today. Renewable energy consumption can reduce carbon emissions (Adebayo et al. 2023) and promote ecological sustainability (Zhang et al. 2022). Therefore, to develop a green economy, key industrial policies have gradually favored renewable energy industries. It has led to a flow of resources from nongreen industries to green industries. Tax policy is another tool for governments to achieve sustainable development, which can effectively improve ecological quality and ensure sustainable development (Ullah et al. 2022). The implementation of both industrial and tax policies, based on a market economy perspective, is prone to market distortions, which in turn affect the efficiency of the market economy (Shayifuga and Deng 2020). Schultz’s human capital investment provides a new way of thinking and a theoretical basis. Modern human capital theory reveals the important role of human capital in improving economic efficiency (Becker 1962; Schultz 1971). Not only does human capital investment help to reduce the production costs of natural resources and save and reduce the use of nonrenewable resources, but it can also significantly increase the utilization of renewable resources and generally improve the quality of natural resource services (Breneman and Schultz 1983). However, few studies have empirically investigated the role of human capital investment in sustainable economic development based on a human capital perspective. Therefore, the first research question examined in this paper is whether an increase in the level of human capital can contribute to GEE and promote green economic development. Given the differences in resource endowments and economic levels between regions, are there regional differences in the impact of human capital on GEE? This is the second research question of this paper. In addition, as industrial policy is tilted toward green-related industries, it will certainly lead to industrial structure upgrading. Does the impact of the human capital level on GEE change with industrial structure upgrading? In other words, does the upgrading of industrial structure have a moderating effect on the human capital-GEE relationship? This is the third research question of this study.

At present, most of the studies on green economic development are based on industry-related perspectives, and less attention has been paid to the potentially important role of human capital. In addition, most scholars have explored the mechanism of the impact of human capital on GEE based on the level of technological innovation, but the degree of matching between human capital and industrial structure upgrading is also an important factor affecting GEE. Furthermore, existing studies mainly focus on the regional and provincial levels, and there is a lack of research at the prefecture level, even though there are significant differences between prefecture-level cities and the provincial and regional levels in terms of the degree of human capital concentration and the degree of implementation of industrial policies. Additionally, there may be differences in the impact on GEE. Therefore, this study aims to examine the impact of the human capital level on GEE and the mechanism of action in each prefecture-level city through 2003–2019 panel data covering 280 prefecture-level cities in China based on the super-efficiency slack-based measure (SBM) model including undesired output to measure GEE.

This paper is structured as follows. In the first section, we introduce the background and the significance of this study. The second section conducts the literature review. The third section describes the methodology, including the variables, data sources and processing, and methods. In the fourth section, we perform an econometric analysis to examine the effect of human capital on GEE. In the fifth section, we discuss the empirical results. In the sixth section, we draw the conclusions and implications.

Literature review

Relevant studies on the impact of human capital on GEE

The most important achievement of modern economic growth has undoubtedly been the increase in the level of human capital (Breneman and Schultz 1983). Scholars have conducted in-depth studies on the impact of the human capital level on economic growth and the mechanisms of its effects. Most studies have shown that human capital can significantly contribute to long-term economic development (Ding et al. 2021; Che Sulaiman et al. 2021; Diebolt and Hippe 2019), based on a large new European dataset, found that regional human capital is an important factor in the current disparities in regional economic development. Ding et al. (2021) used 1990–2013 panel data covering 143 countries and regions to investigate the contribution of human capital versus physical capital to economic growth at different stages. The results showed that human capital can consistently contribute to economic growth. Scholars have validated the importance of human capital for economic growth from different perspectives and based on different regions. However, since it is necessary for countries to develop a green economy and address environmental issues to achieve sustainable development, it is particularly important to enhance GEE. Adebayo et al. (2023) found that renewable energy consumption can reduce carbon emissions and thus increase GEE, and Ullah et al. (2022) found that regulatory environmental taxes are effective in achieving sustainable economic development based on the ecological sustainability of markets or economic measures. Most of the current research on GEE is essentially based on a physical capital-driven perspective (Hudson and Jorgenson 1974), and the importance of human capital for green economic development has not received sufficient attention.

Theoretically, human capital can have a positive effect on GEE and is discussed in two main ways. On the one hand, human capital as a production factor impacts GEE. The Lucas mechanism clarifies the nature of human capital as a direct input factor in the production process (Lucas and Robert 1988). First, the increase in human capital which is a crucial nonphysical factor, and its substitution for physical capital factors in the context of economic transition is an essential means of reducing pollution emissions and can improve green economic performance (Wang et al. 2022). Human capital can maintain a prominent and stable role in different stages of economic development, especially in sustainable economies (Ding et al. 2021). Second, an increase in the level of human capital can improve labor productivity and increase the productivity of other input factors accordingly through its efficiency function. At the same time, it can realize the substitution of other energy factors, which is conducive to improving the efficiency of resource utilization and achieving efficient matching under multiple input factors in production activities, thus promoting GEE (Hudson and Jorgenson 1974). Therefore, human capital can have some positive spillover effects on GEE by increasing labor productivity and the productivity of other factors of production (Sakamoto 2018). On the other hand, because humans are consumers of products, the level of human capital can also lead to green consumption and pollution reduction by influencing the income levels of labor, consumption patterns, and environmental protection perceptions (Ulucak and Bilgili 2018; Chankrajang and Muttarak 2017; Fang and Chen 2017), thus having a significant positive effect on GEE improvement.

In summary, human capital can theoretically impact GEE. In empirical studies, scholars have conducted rich studies based on different measures, regions and scales. However, there is no consistent conclusion regarding the relationship between the human capital and GEE, and further research is needed. Most studies have proven that human capital has a significant positive impact on GEE (Zafar et al. 2021; Wang and Guo 2021 2021; Bano et al. 2018). Xu (2021) found a significant contribution of human capital in the innovation sector to green economic development based on an endogenous growth model and scenario simulation. Guo (2021) investigated the relationship between human capital and regional GEE with intelligent image recognition technology and verified that human capital is an essential driving factor for GEE improvement. Wang et al. (2021) investigated the effect of human capital heterogeneity on GEE by dividing human capital into three levels based on academic education experience and found that the effect of human capital on GEE is significant only at the advanced human capital level with higher academic education, and the sample share was low. The other types of human capital, i.e., primary and secondary education, all have a dampening effect on GEE.

Related studies on the impact of industrial structure upgrading on GEE

Global industrialization leads to an increase in natural resource consumption and pollutant emissions, affecting a country's sustainable development. An industrial structure tilted toward the tertiary sector is an important aspect for improving GEE and promoting sustainable development. Industrial structure upgrading can influence resource allocation efficiency, technical efficiency, and scale efficiency by exerting production factor allocation effects, industrial spillover effects, and specialized division of labor effects, thus impacting GEE (Wang et al. 2021).

First, industrial structure upgrading helps to improve the efficiency of resource utilization by exerting the allocation effect of production factors. Industrial structure upgrading is the process of reallocation of production factors. Under the role of the market, production aspects will automatically flow from inefficient to efficient sectors, and resource utilization efficiency will be improved. In this process, output efficiency will be increased accordingly. As the demand for factors of production in high-efficiency sectors are satisfied, production efficiency increases, and low-efficiency sectors are forced to improve their technology to increase their production efficiency. In addition, there is a mismatch of production factors in China's factor allocation market, which affects the quality of the environment (Ryzhenkov 2016; Yian 2019), while the rational use of resources is the key to energy conservation, pollution reduction and environmental improvement. Therefore, the production factor allocation effect of industrial structure upgrading can promote GEE.

Second, industrial structure upgrading promotes green technological innovation and technological progress by exerting industrial spillover effects to enhance technical efficiency, thus improving GEE (Su and Fan 2022). The specific connotation of industrial structure upgrading is the increase in the proportion of high-tech industries and environmental protection industries. These industries reduce carbon emission intensity and pollution to the environment through their strong technology spillover effect and correlation with other sectors (Jiao et al. 2020), thus contributing to the GEE of different industries.

Finally, industrial structure upgrading improves scale efficiency by realizing the effect of the specialized division of labor, thus improving GEE. With the in-depth development of the product production process, product production gradually requires processing by multiple sectors. To improve efficiency while reducing costs, technological innovation must be carried out in each link to enhance productivity, and industries must gradually develop toward the optimal production scale.

Unfortunately, there are fewer studies that consider industrial structure upgrading as an influencing factor of GEE. In the relevant empirical studies, scholars have found that industrial structure upgrading strongly promoted regional green development (Han et al. 2021) and that the increase in the proportion of the tertiary industry contributed to improving environmental quality (Huang et al. 2018).

Moderating effect of industrial structure upgrading on the human capital-GEE relationship

There is a fitness relationship between human capital and industrial structure upgrading (Hausmann et al. 2007), and the degree of dynamic matching between the two can influence GEE. Human capital and the industrial structure interact and constrain each other (Zhang et al. 2018). Green development will lead to an increase in green technological innovation, on the one hand, and the formation of new industrial forms, on the other hand. When the required human capital support conditions cannot be met, the industrial structure upgrading process will be hindered. Additionally, industrial structure upgrading will be unable to provide the required conditions for human capital, which will make it challenging to achieve human capital accumulation and optimization within industries, thus leading to some human capital idleness (Zhou 2018). Therefore, only a dynamic match between the human capital and industrial structure upgrading can jointly promote GEE.

Relevant studies regarding the impact of human capital on industrial structure upgrading are relatively abundant. Most studies suggest that increasing the level of human capital can promote industrial structure upgrading (Suseno et al. 2020; Wu and Liu 2021). However, there are fewer empirical studies on the relationship between industrial structure upgrading and the human capital-GEE relationship. It is unclear what role the industrial structure plays as a moderating variable in the effect of human capital on GEE.

In summary, current research by scholars in China and elsewhere has provided important contributions and references. At the same time, there are also the following shortcomings. First, there are more studies on the influence of human capital on economic growth. However, in the context of pursuing a win–win situation of economic development and environmental improvement, less attention has been paid to the influence of human capital on GEE, and relevant studies have not reached a consistent conclusion on the relationship between the two. Second, studies on the specific mechanism of the impact of human capital on GEE are mainly focused on the perspective of technological progress, and there is a lack of research on industrial structure upgrading as a moderating variable. Third, most relevant studies focus on the national or provincial scales, and there is a lack of more in-depth studies at the city scale. Since cities are the centers of economic activities and the basic policy-making units, it is crucial to study the city scale for urban development. With China's population concentrated in cities, the urban economy has an increasing impact on the economic growth of the whole country, and green development that reduces carbon emissions and pollutant emissions in urban areas becomes the key to the whole country's ability to improve GEE. Based on 2003–2019 panel data covering 280 prefecture-level cities in China, this study aims to examine the impact of human capital on GEE and to further explore the moderating effect of industrial structure upgrading on the relationship between human capital and GEE, which will contribute to existing research in this field based on the selection of spatial scales and the moderating variable.

Methodology

Variable descriptions and data sources

Explained variables and core explanatory variables

The explanatory variable in this paper is GEE, and data envelopment analysis (DEA) is a very effective method of measuring the efficiency of decision-making units (Charnes et al. 1978). It is also commonly used by scholars to measure

GEE (Song et al. 2020; Guo et al. 2022). DEA is a nonparametric efficiency evaluation method that uses linear programming methods to evaluate whether the same type of multiple-input, multiple-output decision-making units are technically efficient and scale efficient. However, the traditional DEA model suffers from the slackness of the input and output variables. The SBM-DEA model constructed by Tone incorporates slack variables into the objective function, which bett"r so'ves the problem above (Tone 2001). On this basis, this paper measures the GEE of 280 prefecture-level cities in China using the SBM model that includes undesired outputs. The SBM model is as follows:

Assume that the production system has n decision-making units whose input variables, desired outputs, and undesired outputs can be represented as $x \in R_+^m$, $y^g \in R_+^{S_1}$, and $y^b \in R_+^{S_2}$, respectively, and accordingly define the matrices $X=[x_1,\ldots, x_n] \in R^{m\times n}$, $Y^g=[y_1^g,\ldots, y_n^g] \in R^{S_1\times n}$, and $Y^b=[y_1^b,\ldots, y_n^b] \in R^{S_2\times n}$, where $X>0$, $Y^g>0$, and $Y^b>0$. The set of production possibilities P with constant returns to scale can be defined as $P=\{(x, y^g, y^b) | x>X\lambda, y^g>Y^g\lambda, y^b>Y^b\lambda, \lambda \geq 0\}$, where λ is a non-negative weight vector on R_+^n. Then, the SBM model based on constant returns to scale and including undesired outputs can be expressed as follows:

$$\rho^* = \min \frac{1 - \frac{1}{m}\sum_{i=1}^{m} \frac{s_i^-}{x_{i0}}}{1 + \frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1} \frac{s_r^g}{y_{r0}^g} + \sum_{r=1}^{s_2} \frac{s_r^b}{y_{r0}^b}\right)} \tag{1}$$

The model is transformed into a linear programming model as follows:

$$x_0 = X\lambda + s^- \tag{2}$$

$$y_0^g = Y^g\lambda + s^g \tag{3}$$

$$y_0^b = Y^b\lambda + s^b \tag{4}$$

where s^-, s^g, and s^b denote the input, desired output, and undesired output slack variables, respectively, and all are non-negative. The objective function ρ^* is strictly decreasing with respect to s^-, s^g, and s^b, and $0 \leq \rho^* \leq 1$. The decision-making unit is efficient if and only if $\rho^*=1$, that is, $s^-=0$, $s^g=0$, and $s^b=0$. The decision-making unit is inefficient when $\rho^*<1$, i.e., at least one of s^-, s^g, and s^b is not equal to zero. Model (1) is a nonlinear programming model that can be solved by transforming it to a linear programming model through the Charnes–Cooper transformation method.

The measurement indicators are divided into input indicators and output indicators. Among them, the input indicators mainly include labor, capital, and energy. In this paper, we take the approach adopted in most studies and choose the total number of employed persons in each city at the end of the year to represent the labor input, which is expressed as the sum of the total number of unit employees and urban private and self-employed persons at the end of the year. Meanwhile, this paper adopts Goldsmith's perpetual inventory method to calculate the fixed asset stock of each city to represent capital. The specific formula is $K_t=(1-\delta_t)K_{t-1}+I_t/P_t$, where K_t and K_{t-1} represent the capital stock in periods t and $t-1$, respectively, and δ_t, I_t, and P_t are the capital depreciation rate, capital investment, and price index in period t, respectively. Referring to the study of Jun Zhang et al. (2004), we set the capital depreciation rate is set to 9.6%, while the consumer price index of each region is used to denote the price index. The base period capital stock formula is $K_0=I_0(1+g)/(g+\delta)$, where K_0, I_0, g, and δ denote the base period capital stock, the base period capital investment, the geometric mean growth rate of capital investment, and the depreciation rate, respectively. In this paper, 2003 is chosen as the base period for capital stock calculation, and the fixed asset investment amount in each prefecture in 2003 is divided by 10% as the initial capital stock of that prefecture (Chow and Li 2002). There is no depreciation rate in the base period; thus, at this point, $\delta=0$. For energy inputs, the choice of energy variables is statistically based on transforming the consumption of four primary disposable energy sources, i.e., coal, oil, natural gas, and hydropower, into a uniform unit (standard coal) based on the corresponding ratio and then summing them to account for them. However, considering the availability of data at the city level, total social electricity consumption is used to measure the energy input of each city.

The output indicators include desired output and undesired output. In this paper, the GDP of each city is used to represent the desired output. In addition, the industrial wastewater, industrial sulfur dioxide, and industrial smoke (dust) emissions of each city are selected as undesired outputs in this paper.

The core explanatory variable in this paper is the human capital level of each prefecture-level city. Considering the availability of data, this paper expresses the human capital level of each prefecture-level city as the number of higher education undergraduates and college students per 10,000 people (Wang et al. 2022).

Control variables

To avoid the problem of omitted variables, the level of economic development, foreign direct investment (FDI), the industrial structure, city size, environmental regulation, and the STI level are selected as control variables in this paper. The control variables are described specifically in Table 1.

(1) Level of economic development (LPGDP). There is a close relationship between a city's economic growth and its GEE. In this paper, the economic development

Table 1 Description of the control variables

Variables	Description	Measurement	Sources
LPGDP	Level of economic development	Logarithm of GDP per capita (CNY)	China City Statistical Yearbook
FDI	Foreign direct investment	Actual amount of foreign capital used per capita in the year (billion)	China City Statistical Yearbook
Indus	Level of industrialization	Proportion of the output value of the secondary industry in GDP (%)	China City Statistical Yearbook
Size	City size	Logarithm of the urban population size	China City Statistical Yearbook
ER	Environmental regulation	Comprehensive utilization rate of industrial solid waste (%)	China City Statistical Yearbook
TecIn	The STI level	Proportion of science and technology expenditure in the city's GDP (%)	China City Statistical Yearbook

of a city is measured by its GDP per capita. Since there is a significant difference in economic development among cities, GDP per capita is logarithmic in this paper.

(2) Foreign direct investment (FDI). On the one hand, FDI can bring advanced clean technology, promote environmental protection-related technological innovation, and improve resource utilization through demonstration effects, personnel mobility, and industrial linkages, thus promoting GEE (He et al. 2022). On the other hand, according to, "pollution transfer theory," FDI may be detrimental to GEE (Candau and Dienesch 2017). According to the National Bureau of Statistics, manufacturing industries account for 30% of the actual foreign investment in China, which is mostly concentrated in pollution-intensive industries (Dellachiesa and Myint 2016; Sarkodie and Strezov 2019). This paper measures foreign investment per capita (He et al. 2022).

(3) Level of industrialization (Indus). A close link between the level of industrialization and GEE cannot be ignored. In general, the higher the share of the secondary industry, the more pollutants such as sulfur dioxide (SO_2) and respirable particulate matter are produced. The more serious the pollution is, the more harmful it is to GEE. This variable is expressed as the proportion of the output value of the secondary industry in GDP.

(4) City size (Size). The influence of city size on GEE is mainly reflected in two effects (He et al. 2022). One is the agglomeration economic effect, that is, the positive externality of city size. The expansion of city size generates an agglomeration economic effect, through which factors such as labor, capital, and technology flow to the city and economic activities are frequent, thus increasing the agglomeration power of the city (Düben and Krause 2021). The other is the crowding-out effect, which is a negative externality of city size. The expansion of city size increases the demand and consumption of resources such as land, energy, and various public goods. When this demand and consumption reach the threshold of urban capacity, problems such as an insufficient supply of resources and traffic congestion are more prominent. At the same time, the emission of pollutants such as wastewater, waste gas, and solid waste from urban production and life increases (Mohajeri et al. 2015). The deterioration of the urban environment leads to inefficient urban economic growth, and increased resource constraints and environmental pollution can reduce urban GEE. In this paper, this variable is measured by the amount of the urban population and is logarithmic.

(5) Environmental regulation (ER). According to the Porter hypothesis, appropriate environmental regulation can stimulate enterprises' innovation activities (Porter and van der Linde 1995) and enhance product competitiveness, thus improving GEE. However, some studies suggest that environmental regulation will reduce enterprises' research and development (R&D) investment and increase production costs, which is not conducive to GEE. Most studies suggest that environmental regulation has a significant U-shaped effect on green economic development (Zhao et al. 2022). The literature generally uses pollution control investment (McConnell and Schwab 1990) and the environmental regulation composite index (He et al. 2022) based on the "three waste" removal rate to measure environmental regulation. However, since the relevant data are unavailable at the city level in China, this paper refers to Lin and Tan (2019). Their methods use the comprehensive utilization rate of industrial solid waste to measure the degree of environmental regulation.

(6) The level of science and technology innovation (TecIn). The STI level is also an essential factor affecting GEE (Cao et al. 2022). According to endogenous economic growth theory, higher enterprise the R&D investment is better for promoting technological innovation and technological progress and thus improves the productivity of enterprises and GEE. Technology expenditure costs are the basis for effective innovation in science and technology, and capital investment in R&D can directly affect the level of local STI. Based on data

availability, this paper uses the proportion of science and technology expenditure in the city's GDP.

Data description

This paper selected data covering 280 prefecture-level cities in China from 2003 to 2019. The data required for the variables were obtained and collated from the China Statistical Yearbook and China City Statistical Yearbook. The missing sample data from 2003 to 2019 were filled in through interpolation before the baseline regression was conducted.

The results of the variables and the descriptive statistics of the data in the paper are shown in Table 2. Figure 1 shows the scatter plot of the relationship between the human capital level and GEE. From the figure, we tentatively determine a positive correlation between the two, which is consistent with the underlying theory.

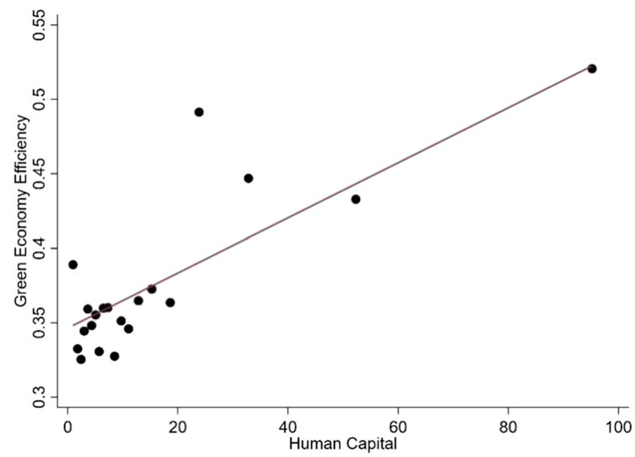

Fig. 1 Scatterplot of the human capital level and GEE

Empirical analysis

Baseline regression results

To examine the effect of the human capital level on GEE, the benchmark econometric model in this paper is as follows:

$$GE_{it} = \alpha_0 + \alpha_1 Human_{it} + \alpha_2 Z_{it} + \rho_t + \eta_i + \varepsilon_{it} \tag{5}$$

where GE_{it} denotes the GEE level of prefecture-level city i in year t; $Human_{it}$ denotes the human capital level of prefecture-level city i in year t; Z_{it} denotes the control variables at the level of the prefecture-level city; ρ_t and η_i represent the time fixed effect and city (prefecture-level city) fixed effect, respectively; and ε_{it} is the error term.

Columns (1), (2), and (3) of Table 2 indicate the overall regression results of the stepwise inclusion of the time and city fixed effects and the control variables, respectively. The regression results show a significant positive impact of human capital on improving urban GEE. An increase of 0.1‱ in the share of the number of undergraduates increases GEE by 0.001. This result implies that a higher percentage of the population with a higher level of education is more conducive to improving GEE. Human capital can drive technological innovation, improve energy efficiency, and reduce pollutant emissions, thereby increasing GEE. This result is in line with most existing studies (Zafar et al. 2021; Bano et al. 2018), which find that human capital can reduce carbon emissions. Wang and Guo (2021) concluded that human capital positively affects GEE. Wang and Xu (2021) concluded that only human capital with higher education can contribute to local GEE, while human capital with primary education acts as a disincentive. Shayifuga and Deng (2020) found an inverted U-shaped relationship between human capital and GEE. In addition, the coefficients of GDP per capita, the FDI level and the industrialization level are significant at the 0.01 level.

GDP per capita has a positive and significant effect on GEE, with each 1% increase in log GDP per capita increasing the level of GEE by 0.048%. The study shows that the degree of economic agglomeration is within a specific range, which is conducive to GEE. When the degree of economic aggregation exceeds a critical value, there is a negative effect (Lin and Tan 2019). This result indicates that China's current

Table 2 Descriptive statistics of the variables

Variables	Units	Sample size	Mean	Variance	Min	Max
GE	-	4760	0.376	0.249	0.0608	1.330
Human	0.1‱	4760	16.04	22.59	0.0592	350.2
LPGDP	CNY	4466	10.16	0.837	4.595	13.06
FDI	Billion	4588	5.894	12.24	0.0002	140.0
Indus	%	4760	41.90	15.67	0.590	84.65
Size	per	4760	5.844	0.678	2.795	9.315
ER	%	4635	0.781	0.270	0.0024	9.950
TecIn	%	4760	11.67	2.188	−0.247	18.16

degree of economic agglomeration is still within a reasonable range, which can promote the local GEE level.

The effect of FDI on GEE is significant at the 1% level. The level of GEE increases by 0.002 per 100 million CNY increase in FDI. A high level of FDI indicates that more foreign enterprises are entering. Foreign enterprises generally have more advanced energy-saving and emission-reduction technology and higher green management levels, which is conducive to green industrial agglomeration and reduces the number of domestic green enterprises through the innovation costs brought by spillovers (Khachoo and Sharma 2016), thus increasing the level of green innovation of enterprises and thus improving GEE.

The level of industrialization negatively and significantly affects GEE. This result indicates that an increase in the share of the secondary sector is not conducive to improving GEE. A higher industrialization level means a more significant proportion of industries with high energy consumption, high pollution, and high emissions, which increases the emission of pollutants and thus has a negative impact on GEE.

City size positively affects GEE. Existing studies show that city size has a nonlinear effect on GEE (Molayi et al. 2015). City size expansion can generate agglomeration effects and enhance the agglomeration of cities (Düben and Krause 2021). Negative externalities arise when the size of a city exceeds the city's accommodation threshold, the resource supply is insufficient, and traffic congestion gradually becomes prominent. The results of this paper show that the current degree of population concentration in China is still not high enough to have a positive effect on GEE.

Environmental regulation negatively affects the level of GEE. This result indicates that environmental regulations, while correcting negative environmental externalities, also impose additional burdens on enterprises, which negatively impact the economic efficiency of enterprises, sectors or regions (Gray 1987).

The STI level positively affects GEE. An increase in the STI level can improve resource utilization efficiency, thus helping reduce excessive pollutant emissions due to resource waste, positively affecting GEE. In addition, an increase in the STI level requires more human capital input, and the substitution effect of human capital on other factors can reduce the input use of natural materials and resources, promoting the GEE.

Analysis of regional differences

The level of GEE is influenced by factors such as the economic level, FDI, environmental regulation, the industrial structure, and human capital (Hu et al. 2019; Liang et al. 2019; Wang et al. 2021). These factors differ significantly in Eastern, Central, and Western China. In this regard, the regional imbalance in the human capital level is significant (Heckman 2003), which may be an essential factor leading to the regional disparities in GEE among regions. Therefore, to examine the regional differences in the impact of human capital on GEE, this paper divides the research sample into three regions: Eastern, Central, and Western China. Details on the cities in the eastern, central, and western regions are given in the Appendix. The regression results are shown in the columns (4)–(6) of Table 3.

The coefficients of GDP per capita, city size, and the STI level do not pass the significance test and are not statistically significant. In contrast, the coefficient of FDI is 0.002 and is statistically significant at the 1% level. The coefficient of the industrialization level is −0.003 and passes the significance test at the 1% level. Therefore, the eastern region's GDP per capita, city size, and STI level are not significant. At the same time, FDI significantly and negatively affects GEE, and the industrialization level positively affects GEE. These are the main factors affecting GEE in the eastern region.

Human capital positively affects the GEE of the central region, but it is not statistically significant. The coefficients of GDP per capita and FDI are 0.082 and 0.002, respectively, and are significant at the 1% and 5% levels, respectively. The coefficient of city size is 0.014, but it is statistically nonsignificant. The coefficient of the industrialization level is significantly negative, and the coefficients of environmental regulation and the STI level are negative but statistically nonsignificant. Thus, GDP per capita and the FDI level are the main influencing factors of GEE in the central region.

Human capital positively affects GEE in the western region, but it is statistically nonsignificant. The coefficient of GDP per capita is 0.019, but statistically nonsignificant. The coefficients of FDI and environmental regulation are 0.003 and 0.058, respectively, and are significant at the 1% and 5% levels, respectively. The coefficients of the industrialization level and city size are −0.002 and −0.244, respectively, and are significant at the 1% level. The coefficient of the STI level is negative and statistically nonsignificant. Therefore, FDI, environmental regulation, the industrialization level, and city size are the main factors affecting GEE in the western region.

Robustness tests

It is usually believed that human capital can improve GEE. Conversely, improving GEE in the current period may push cities to attract more human capital and promote the level of human capital in cities. That is, there may be a significant two-way causal relationship between human capital and GEE, thus causing an endogeneity problem. To solve this problem, this paper introduces a one-period lag of GEE into the model, takes human capital and GEE as endogenous variables, takes lags of order 2

Table 3 National and subregional regression results

Variables	National	National	National	Eastern	Central	Western
Human	0.002***	0.001***	0.001***	0.002***	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)
LPGDP			0.046***	0.026	0.082***	0.019
			(0.014)	(0.025)	(0.023)	(0.020)
FDI			0.002***	0.002***	0.002**	0.003***
			(0.000)	(0.001)	(0.001)	(0.001)
Indus			−0.002***	−0.003***	−0.000	−0.002***
			(0.000)	(0.001)	(0.001)	(0.001)
Size			0.012	0.017	0.014	−0.244***
			(0.010)	(0.017)	(0.012)	(0.076)
ER			−0.013	−0.051	−0.023	0.058**
			(0.008)	(0.032)	(0.014)	(0.026)
TecIn			−0.000*	−0.000	−0.000**	−0.000
			(0.000)	(0.000)	(0.000)	(0.000)
Constant	0.346***	0.361***	−0.098	0.263	−0.592**	1.581***
	(0.004)	(0.005)	(0.155)	(0.308)	(0.239)	(0.446)
City FE	No	Yes	Yes	Yes	Yes	Yes
Year FE	No	Yes	Yes	Yes	Yes	Yes
F	91.15***	10.65***	10.69***	7.43***	3.82***	6.76***
R^2	0.028	0.752	0.789	0.808	0.700	0.752
Observations	4760	4760	4199	1515	1516	1168

*, **, and *** indicate significance at the 10%, 5% and 1% levels, respectively, with robust standard errors in parentheses. The same applies below

to 3 as instrumental variables, and constructs a two-stage systematic generalized method of moments (GMM) model for estimation. The specific results, which are presented in Table 4, show that the values of AR (1) in the national model and the eastern, central and western subregional models are less than 0.05 and pass the significance test at the 1% level. The values of AR (2) in the national model and the eastern, central and western subregional models are 0.860, 0.832, 0.124, and 0.460, respectively, all of which are greater than 0.1 and fail the significance test, which is consistent with the hypothesis of serial uncorrelatedness in GMM estimation. In this paper, N is much larger than the number of instrumental variables; thus, the Hansen test is chosen to test the validity of the instrumental variables. The results in the Table 4 show that the Hansen test results for the four models are 0.248, 0.497, 0.233, and 0.265, which are all greater than 0.05 and less than 0.3. Thus, the hypothesis that all instrumental variables in the model are valid is accepted. From the model estimation results, the core explanatory variable human capital significantly and positively affects the level of GEE in the national model and eastern subregion models, while it has a positive but nonsignificant effect on GEE in the central and western subregion models. The regression results remain consistent with the static panel data model, which verifies the robustness of the study findings.

Moderating effects

According to Clark's theory of allotment, the labor force shifts between industries from the primary industry to the secondary and tertiary industries. The industrial structure gradually changes from labor-intensive industries to capital-intensive or knowledge-intensive industries. Industrial structure upgrading then develops the economy mainly through capital-intensive or knowledge-intensive industries and increases the proportion of the tertiary industry, affecting GEE. Therefore, the appropriateness of human capital and the industrial structure is the key to upgrading the efficiency of the industrial structure. There is a dynamic matching effect between human capital and industrial structure upgrading (Hausmann et al. 2007). Therefore, industrial structure upgrading may act synergistically with human capital and affect urban GEE. To further verify the moderating effect of industrial structure upgrading on the human capital-GEE relationship, the following empirical model is constructed in this paper:

$$GE_{it} = \alpha_0 + \alpha_1 HT_{it} + \sum \alpha_n Z_{itn} + \rho_t + \eta_i + \varepsilon_{it} \quad (6)$$

$$HT_{it} = Human_{it} \times TS_{it} \quad (7)$$

Among them, TS_{it} is the industrial structure upgrading, usually expressed as the ratio of the output of the tertiary industry to the output of the secondary industry. HT_{it}

Table 4 Results of robustness tests

Variables	National	Eastern	Central	Western
Human	0.001**	0.002**	0.001	0.001
	(0.000)	(0.001)	(0.001)	(0.001)
L.GE	0.641***	0.652***	0.669***	0.637***
	(0.072)	(0.075)	(0.100)	(0.103)
LPGDP	−0.019	−0.010	0.003	−0.025
	(0.016)	(0.022)	(0.013)	(0.016)
FDI	−0.000	0.001	−0.001	0.000
	(0.002)	(0.002)	(0.001)	(0.003)
Indus	−0.001	−0.002	−0.002	0.001
	(0.001)	(0.002)	(0.002)	(0.002)
Size	0.020	−0.016	0.020	−0.074
	(0.034)	(0.044)	(0.033)	(0.049)
ER	−0.206**	−0.149	−0.258***	0.011
	(0.095)	(0.140)	(0.092)	(0.075)
TecIn	0.000	−0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Constant	0.362	0.566	0.255	0.726**
	(0.240)	(0.351)	(0.292)	(0.354)
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
AR(1)	0.000	0.000	0.001	0.001
AR(2)	0.860	0.832	0.124	0.460
Hansen test	0.248	0.497	0.233	0.265
Observations	3941	1418	1420	1103

** and *** indicate significance at the 10%, 5% and 1% levels, respectively, with robust standard errors in parentheses. The same applies below

denotes the cross-term of the human capital level and industrial structure upgrading. Considering the possible covariance between the industrialization level and industrial structure upgrading, the control variables in this section remove the industrialization level (Indus), and the rest of the control variables are consistent with the "Discussion" section. In addition, the cross-term is prone to multiple cointegration problems. Therefore, this section solves these problems by generating the cross-term after centering on human capital and industrial structure upgrading.

Columns (1), (2), and (3) of Table 5 indicate the regression results of gradually adding the time and city fixed effects and the control variables, respectively. The results show that without adding any control variables or fixed effects, the effect of the human capital level on GEE is significantly positive. The cross-term of the human capital level and industrial structure upgrading has a significantly positive effect on GEE, which indicates that industrial structure upgrading strengthens the negative relationship between the human capital level and GEE. The results in column (2) are the regression results that include the city and time fixed effects. The results indicate that industrial structure upgrading strengthens the impact of human capital on GEE. The results in column (3) are the regression results after adding the city and time fixed effects and the control variables. The coefficient of human capital is 0.001, and the coefficient of the cross-term between human capital and industrial structure upgrading is also 0.001, and both are significant at the 5% level. Figure 2 shows the schematic diagram of the effect of industrial structure upgrading on the impact of human capital on GEE. It indicates that industrial structure upgrading significantly contributes to the relationship between the human capital level and GEE.

Discussions

Higher levels of human capital contribute to GEE in prefecture-level cities in China

Human capital is a key factor in achieving a green transformation of the economy. First, human capital is the basis for promoting technological innovation and helps the development and application of advanced green technologies. On the one hand, this facilitates the efficiency of utilization among various factors

Table 5 Regression results of the moderating effect of industrial structure upgrading

Variables	(1)	(2)	(3)
HT	0.002***	0.000	0.001**
	(0.000)	(0.000)	(0.000)
Human	0.001***	0.001***	0.001**
	(0.000)	(0.000)	(0.000)
TS	0.024**	0.011	0.018
	(0.010)	(0.011)	(0.019)
LPGDP			0.042***
			(0.016)
FDI			0.002***
			(0.000)
Size			0.008
			(0.009)
ER			−0.012
			(0.009)
TecIn			−0.000*
			(0.000)
Constant	0.375***	0.380***	−0.090
	(0.004)	(0.002)	(0.170)
City FE	No	Yes	Yes
Year FE	No	Yes	Yes
F	39.71	4.74	6.88
R^2	0.044	0.761	0.788
Observations	4470	4470	4196

*, **, and *** indicate significance at the 10%, 5% and 1% levels, respectively, with robust standard errors in parentheses. The same applies below

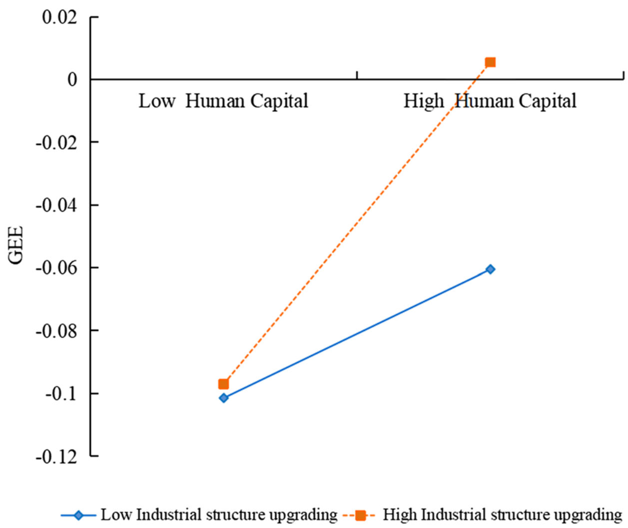

Fig. 2 Schematic diagram of the moderating effect

of production and energy and, on the other hand, improves the efficiency of substitution of environmental factors for polluting factors, which in turn reduces the level of energy consumption and pollution emissions and has an impact on GEE. Specifically, a high level of human capital can improve a region's labor productivity. The marginal contribution of human resources with high levels of human capital to production is higher than that of the average labor force. In contrast, the trend of lower marginal productivity is moderated by the increase in the utilization efficiency between each factor of production and energy (Sabadie 2014). Second, higher levels of human capital are conducive to stimulating green demand and production and forming a sound green consumption structure. An increase in the level of regional human capital is followed by a rise in resource conservation and environmental awareness (Consoli et al. 2016), which enables residents to be guided by high-level talent and to gradually realize the disadvantages of traditional production and consumption methods for ecological and environmental sustainability, further favoring the formation of green consumption concepts. Finally, the relative income of high-level human capital is higher. The willingness to pay for environmentally friendly products is stronger (Shao et al. 2018). The formation of this consumption structure is likely to influence the investment decision of enterprise products and the formation of the green production concept, thus improving the local GEE. This result is in line with existing studies (Wu and Liu 2021; Cai et al. 2020; Haraguchi et al. 2019), which note that the green effect of human capital gradually increases as the level of industrialization increases.

There are regional differences in the impact of human capital on GEE

For the eastern region, human capital significantly and positively affects regional GEE and, in terms of coefficients, twice as much as at the national level. However, this effect is not significant in the central and western regions. This result may be because human capital is more concentrated in the eastern region than in the central and western regions, and the accumulation of human capital, to a certain extent, may impact GEE (Huang et al. 2018). The eastern region is highly attractive to high-level human capital due to its significant geographical location advantage (He et al. 2022). This concentration of high-level human capital is responsible for the local knowledge and technology level of the region, which increases enterprises' production efficiency and level of process orientation, and resources are fully utilized, contributing to GEE. For the central and western regions, human capital does not match these regions' economic structure, and low human capital has a lower impact on the local production structure. The unsound labor market will also constrain human capital in the central and western regions. Thus, the effect of human capital on GEE in the western and central regions is lower.

Industrial structure upgrading plays a positive moderating role in the human capital-GEE relationship

Specifically, the match between human capital and industrial structure upgrading can impact GEE in prefecture-level cities. This result is consistent with the findings of existing research (Wu and Liu 2021). The higher the degree of the match between human capital and industrial structure upgrading, the more conductive it is to the effective use of resources and the reduction in resource waste and pollutant emissions, thus improving the GEE of cities (Haraguchi et al. 2019). In the transformation of economic green development, regions have a greater demand for the influx of technical knowledge brought by high-level human capital. At this time, in the process of human capital positively contributing to local GEE, local industrial structure upgrading can sufficiently boost human capital. Industrial structure upgrading also brings particular convenience to the introduction of human capital, which is conducive to further improving the human capital level. Additionally, this will also form a trend in which human capital and industrial structure upgrading continuously select each other, thus contributing to the sustainable improvement in local GEE.

Conclusions and policy implications

Conclusions

In the empirical part, we use 2003–2019 panel data covering 280 prefecture-level cities in China to calculate GEE, including undesired output, based on the super-efficiency SBM model to explore the impact of the human capital level on GEE and the moderating effect of industrial structure upgrading on the human capital-GEE relationship in each prefecture-level city. First, we explore the relationship between the level of human capital and GEE at the prefecture level, and the results show that an increase in the level of human capital at the prefecture level contributes to the improvement in GEE. Second, we divide the sample into three regions, Eastern, Central, and Western China, to explore whether there are regional differences in the impact of human capital on GEE. We find that there are regional differences in the effect of the human capital level on GEE, with a significant positive impact on GEE in the eastern region and a positive but nonsignificant effect in the central and western regions, These results may be due to the high degree of population concentration in the eastern region compared to the central and western regions. The role of each factor in regional GEE also varies in different regions. FDI and the industrialization level are the main factors influencing GEE in the eastern region; GDP per capita and FDI are the main factors influencing GEE in the central region; and FDI, environmental regulation, the industrialization level, and city size are the main factors affecting GEE in the western region. Third, to further investigate the mechanism of the impact of human capital on GEE, this paper incorporates the cross-term between industrial structure upgrading and human capital into the regression model. The analysis shows that industrial structure upgrading plays a moderating role in the human capital-GEE relationship. That is, industrial structure upgrading can strengthen the mechanism of the impact of the human capital level on GEE.

Policy implications

First, the empirical analysis above shows that high levels of human capital can significantly improve local GEE. However, in China, as in other developing countries, the overall level of human capital, as well as the talent pool and human capital investment related to the environmental protection industry, is seriously insufficient, and the relevant talent training system and policy support are still in their infancy. Therefore, on the one hand, local governments should build on the existing human capital training system, increase their investment in education, and strengthen the training of high-level human capital across industries. On the other hand, the government should accelerate the cultivation of social organizations in the field of green development; assist local governments in popularizing and promoting the participation of community residents in climate change with the power and resources of social organizations; encourage social organizations to develop specialized and socialized training in the fields of clean production, energy conservation, emission reduction, and green consumption by using government procurement after financial subsidies; and build a training system for the government, universities, industrial alliances, and enterprises. In addition, the government should promote the training system of green development population capital in universities. The government should also promote industry-academia-research cooperation and talent training in the field of green development in universities to provide more specialized talent for the public and private sectors in China's response to climate change.

Second, the government should fully consider the geographical characteristics of locations, take targeted measures based on the actual reality of local development, and implement differentiated talent support strategies. The eastern region should continue to take advantage of its talent leadership, take advantage of the concentration of human capital and various production factors, improve its technological innovation, and realize green production. The central and western regions should pay attention to matching human capital with the local economic structure, improve their local infrastructure facilities while promoting strategies related to talent introduction, and continuously improve the labor market to encourage the sustainable development of the green economy.

Third, as an essential factor of human capital for GEE, industrial structure upgrading is a key driving force in realizing the transformation of regional green economic development. Therefore, full play should be given to the role of local human capital to improve technological innovation capacity, especially in the areas of energy conservation, water conservation, environmental protection, and renewable energy, and to promote the upgrading of the local industrial structure in concert with the government's supporting industrial policies. High technology should be used to address the disadvantages of high pollution, high energy consumption, and inadequate resource utilization in traditional manufacturing industries and to continuously promote green production methods. In addition, policies can tend to incentivize the import of environmentally friendly technologies and promote the introduction of green technologies through policy support as well as tariff adjustments to improve energy efficiency, thereby promoting the integration of green industries and the upgrading of the industrial structure and thus improving GEE and promoting the sustainable development of the green economy.

Based on existing research, this paper explores the impact of human capital on GEE and regional differences at the level of prefecture-level cities, and it examines the moderating effect of industrial structure upgrading on the human capital-GEE relationship by constructing a moderating effect model. However, there are still some limitations in this study, and further consideration and research can be conducted regarding the following aspects in future studies: first, in quantifying human capital, industrial structure upgrading, and GEE, the existing research methods, indicator systems, and data sources are not yet unified, and indicators, data, and methods that are more in line with the national conditions can be further explored in future studies to continuously enrich the methods for quantifying indicators. Second, in terms of the mechanism of action, this study only tested the moderating role of industrial structure upgrading, but what other paths exist for the impact of human capital on the efficiency of the green economy still need further analysis and research. Third, economic activities and human capital have certain spatial characteristics, and subsequent studies can consider introducing spatial factors to examine the influence of human capital on GEE and its mechanism of action.

Appendix

The eastern region includes 97 prefecture-level cities: Shijiazhuang, Tangshan, Qinhuangdao, Handan, Xingtai, Baoding, Zhangjiakou, Chengde, Cangzhou, Langfang, Hengshui, Shenyang, Dalian, Anshan, Fushun, Benxi, Dandong, Jinzhou, Yingkou, Fuxin, Liaoyang, Panjin, Tieling, Chaoyang, Huludao, Nanjing, Wuxi, Xuzhou Changzhou, Suzhou, Nantong, Lianyungang, Huai'an, Yancheng, Yangzhou, Zhenjiang, Taizhou, Suqian, Hangzhou, Ningbo, Wenzhou, Jiaxing, Huzhou, Shaoxing, Jinhua, Quzhou, Zhoushan, Taizhou, Lishui, Fuzhou, Xiamen, Putian, Sanming, Quanzhou, Zhangzhou, Nanping, Longyan, Ningde, Jinan, Qingdao Zibo, Zaozhuang, Dongying, Yantai, Weifang, Jining, Taian, Weihai, Rizhao, Linyi, Dezhou, Liaocheng, Binzhou, Heze, Guangzhou, Shaoguan, Shenzhen, Zhuhai, Shantou, Foshan, Jiangmen, Zhanjiang, Maoming, Zhaoqing, Huizhou, Meizhou, Shanwei, Heyuan, Yangjiang, Qingyuan, Dongguan, Zhongshan Chaozhou City, Jieyang City, Yunfu City, Haikou City, Sanya City.

Central region includes 100 prefecture-level cities: Taiyuan, Datong, Yangquan, Changzhi, Jincheng, Shuozhou, Jinzhong, Yuncheng, Xinzhou, Linfen, Lvliang, Changchun, Jilin, Siping, Liaoyuan, Tonghua, Baishan, Songyuan, Baicheng, Harbin, Qiqihar, Jixi, Hegang, Shuangyashan, Daqing, Yichun, Jiamusi, Qitaihe, Mudanjiang, Hehe, Suihua, Hefei, Wuhu, Bengbu, Huainan, Maanshan, Huaibei, Tongling, Anqing, Huangshan, Chuzhou, Fuyang, Suizhou, Liuan, Bozhou, Chizhou, Xuancheng, Nanchang, Jingdezhen, Pingxiang, Jiujiang, Xinyu, Yingtan, Ganzhou, Ji'an, Yichun, Fuzhou, Shangrao Zhengzhou, Kaifeng, Luoyang, Pingdingshan, Anyang, Hebi, Xinxiang, Jiaozuo, Puyang, Xuchang, Luohe, Sanmenxia, Nanyang, Shangqiu, Xinyang, Zhoukou, Zhumadian, Wuhan, Huangshi, Shiyan, Yichang, Xiangyang, Ezhou, Jingmen, Xiaogan, Jingzhou, Huanggang, Xianning, Suizhou, Changsha, Zhuzhou, Xiangtan Hengyang, Shaoyang, Yueyang, Changde, Zhangjiajie, Yiyang, Chenzhou, Yongzhou, Huaihua, Loudi.

Western region includes 83 prefecture-level cities: Hohhot, Baotou, Wuhai, Chifeng, Tongliao, Erdos, Hulunbeier, Bayannur, Ulanqab, Nanning, Liuzhou, Guilin, Wuzhou, Beihai, Fangchenggang, Qinzhou, Guigang, Yulin, Baise, Hezhou, Hechi, Laibin, Chongzuo, Chengdu, Zigong, Panzhihua Luzhou, Deyang, Mianyang, Guangyuan, Suining, Neijiang, Leshan, Nanchong, Meishan, Yibin, Guang'an, Dazhou, Ya'an, Bazhong, Ziyang, Guiyang, Liupanshui, Zunyi, Anshun, Kunming, Qujing, Yuxi, Baoshan, Zhaotong, Lijiang, Pu'er, Lincang, Xi'an, Tongchuan, Baoji, Xianyang, Weinan, Yan'an, Hanzhong, Yulin, Ankang, Shangluo, Lanzhou, Jiayuguan, Jinchang, Baiyin, Tianshui, Wuwei, Zhangye, Pingliang, Jiuquan, Qingyang, Dingxi, Longnan, Xining, Yinchuan, Shizuishan, Wuzhong, Guyuan, Zhongwei, Urumqi, Karamay.

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