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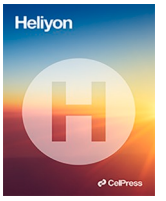

Research article

The impact of innovative human capital on green growth convergence in China's regions from the perspective of space

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ABSTRACT

The convergence of green growth is not only very important for the sustainable development of mankind, but also plays a key role in the coordinated development of eastern, Midwest regions of China. The effect of innovative human capital (IHC) on the convergence of regional green growth in China needs to be explored. This paper empirically explores the impact of IHC on the convergence of regional green growth in China from spatial perspective for the first time. Through the regression analysis of the convergence models, three main conclusions are obtained: (1) there are obvious conditional β space convergence characteristics of green growth among inter-provincial units in China. Under the spatial correlation expressed by distance weights and adjacent weights, the conditional β space convergence characteristics of green growth are quite different. (2) Compared with the adjacency weight, under the distance weight, the spatial diffusion effect of innovative knowledge and technologies created by IHC is stronger. (3) There is club convergence of green growth in the East and the Midwest regions, and the quantity and quality of IHC in the Midwest region play a stronger role in the convergence of green growth than in the East region. Based on the above conclusions, this paper proposes some policies for the East and Midwest regions.

1. Introduction

In order to avoid further environmental degradation around the world, economic growth must follow the principles of sustainable development [1–4]. Climate change events such as floods and droughts have adversely affected agricultural practices, jeopardized food security, and led to population displacement [5]. How to deal with the problems caused by climate change to achieve sustainable development is a great challenge that the world must address. Sustainable development requires consideration of both development and sustainability [6,7]. For the sustainable development of mankind, green growth has replaced the polluting growth of the past as the mainstream trend of development. The concept of green growth proposed by OECD is widely recognized worldwide, and its meaning refers to promoting economic growth and development while ensuring that natural assets can continue to provide various resources and environmental services for human well-being [8].

For measuring the level of green growth in different countries and regions, OECD has also constructed a system of green growth monitoring indicators [9]. In addition to the OECD, the green economic indicator system proposed by UNEP [10], the comprehensive green Growth diagnostic indicator system proposed by Global Green Growth Institute [11] and the 2018 Global Green Economy Index (GGEI) [12] are relatively representative and applicable on a global scale.

Using green growth monitoring indicators and statistical data from OECD, Rocho'n analyzed the level of green growth in 130

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countries from 1990 to 2019 and his research found that these countries formed two green growth convergence clubs: Club 1, consisting of 112 countries, and Club 2, consisting of 18 countries, and that the rate of convergence of club 1 is faster than club 2 because most of the countries in Club 2 belong to the world's major oil-producing countries [13]. The energy transition from traditional fossil energy sources to non-fossil energy sources is the key to achieving green growth [14,15]. The energy transition facilitates the reduction of undesired outputs, particularly greenhouse gas emissions such as carbon dioxide [16].

The energy transition cannot be achieved without technical support. Information and communication technology is conducive to improving the efficiency of energy utilization, but whether ICT can curb carbon dioxide emissions is closely affected by the degree of trade openness and financial development of an economic entity [17]. With the rapid development of technology, artificial intelligence can facilitate the energy transition and reduce carbon emissions, with trade openness playing a mediating role in this process [18]. However, Qiang Wang et al. (2024) pointed out that scholars have mainly explored the impact of trade openness on carbon emissions, but ignored the impact of trade diversification, and found through empirical research that trade openness leads to an increase in carbon emissions, while trade diversification leads to a decrease in carbon emissions [19]. Of course, the factors affecting carbon emissions are comprehensive including not only energy, but also political and social factors such as geopolitical risks, corruption governance and natural resource rents, and the relationship between these factors and carbon emissions is consistent with the assumptions of the environmental Kuznets curve (EKC) [20].

While the factors influencing green growth vary from country to country, in general, the world will become greener, especially with populous countries such as China, India, Brazil, and Indonesia showing good green growth trends [13]. China is the world's second largest economy and the world's largest developing country, as well as the world's largest carbon emitter. China's level of green growth has a very important impact on global and its own sustainable development, and scholars from all countries are concerned about China's green growth status. Through increasingly intensive energy conservation and emission reduction measures, China has successfully entered the global green growth convergence club [13]. The concept of convergence originates from the neoclassical growth theory founded by Solow in 1956, which means that due to the diminishing marginal returns to capital, the rate of economic growth of different economic units (countries or regions) is negatively correlated with the conditions of their initial static indicators, i.e., the lower the initial per capita gdp is, the faster it will converge to the equilibrium point [21].

As China's economic development has entered a new normal, the main contradiction it faces has become "the contradiction between the people's growing needs for a better life and unbalanced and inadequate development". One of the main aspects of "unbalanced and insufficient development" is the uneven level of economic and social development among different regions, which is mainly manifested in the large gap between the central and western parts of the country and the eastern part of the country; therefore, realizing the coordinated development of the three major regions is a major issue that the Chinese government must address.

As a responsible large country, China's coordinated development between different regions is also carried out in accordance with the principle of green growth. Instead of mainly examining the impact of various factors on green growth as in the previous literature, studies on China's green growth status have evaluated China's green growth level based on different green growth indicator systems [22–25]. It can be seen that domestic and foreign scholars still do not have enough research on the influence of factors on the convergence state of China's green growth, Even the aforementioned literature on the factors influencing green growth focuses mainly on energy transition, free trade, geopolitics, technological innovation, etc., and to a certain extent ignores the impact of human capital, which has the title of "first capital".

The 21st century is the era of knowledge economy, and intellectual capital is a key element in determining an organization's competitive advantage and reflects the full value of the organization's intangible assets, including human capital [26]. From a macro perspective, intellectual capital, especially human capital, determines a country's competitive advantage to a large extent. Meanwhile, the 21st century is also the era of green development, and the study of strengthening the impact of human capital on green growth convergence has far-reaching significance and value for the coordinated development of China and the world. The research in this paper can, to a certain extent, make up for the shortcomings of existing research and make the theory on human capital and economic growth richer, and at the same time, the conclusions and countermeasures of this paper are to a certain extent conducive to the Chinese government's efforts to solve the major contradictions existing in the current socioeconomic development.

The rest of the paper consists of the following: the second part is the theoretical background; the third part is the Literature review and hypotheses development; the fourth part is the methodology; the fifth part is results; the sixth part is discussion and the last part is conclusion.

2. Theoretical background

2.1. The introduction of human capital has contributed to the development of growth theories

It is widely recognized that the Solow-Swan model is the real theoretical starting point for the convergence of economic growth. In the mid-to-late 1950s, the American economist Robert Solow and the British economist Trevor Swan constructed an equilibrium economic model to study the growth problem, which has been referred to by later scholars as the "Solow-Swan model". Solow put forward five important assumptions in the construction of the model: (1) the existence of a closed economy; (2) all savings within the economy used to invest; (3) the constant returns to scale of production; (4) only two factor inputs, capital and labor, and diminishing returns at the margin; (5) capital, labor and the two factors of production can be substituted for each other. The general form of the production function in the Solow model is as follows:

$$Y(t) = A(t)F(K(t), L(t)) \tag{1}$$

in equation (1), Y is the total output of the economy, A means the level of production technology, K means all the capital invested in production, L means all the labor invested in production, AL means effective labor, and t denotes time. Here, Solow actually adopts the form of the Cobb-Douglas production function. The key assumption of diminishing marginal returns to capital led neoclassical growth theory scholars represented by Solow to believe that there are two cases of absolute and conditional convergence in economic growth. However, many scholars later found in the empirical research, in a longer period of time, the economic growth of some poor countries is very slow or even stagnation, and there is no convergence; the empirical test between the rich countries shows that the convergence rate calculated on the basis of the model is much faster than that in reality, which reflects the contradiction between empirical research and theoretical analysis, and indicates that the Solow-Swan model is flawed in some aspect. With the establishment of the corresponding endogenous economic growth model by Romer and Lucas respectively in the study of economic growth problems, human capital was introduced into the production function as a brand new production factor. The Cobb-Douglas production function after the introduction of the human capital takes the following form:

$$Y = AK^{\alpha}H^{\beta}L^{\gamma} \tag{2}$$

in equation (2), Y denotes total output, A denotes the level of technology, K denotes material capital, H denotes human capital, and L denotes labor; α, β, and γ denote the output elasticities of material capital, human capital, and labor, respectively. The theory of endogenous economic growth based on human capital has enabled contemporary scholars to gain a deeper understanding of economic growth and its convergence.

2.2. Analysis of the mechanisms by which IHC influences green growth convergence

As theoretical research continues to deepen, the mechanism by which IHC contributes to the convergence of green growth is becoming clearer. This mechanism can be generally summarized in three aspects:

(1) IHC impacts on the quality of the workers with IHC have a strong learning ability, and are far more capable of mastering, applying and reinventing new technologies than ordinary workers. If a relatively backward country or region obtains a larger amount of IHC, it means that the quality of its labor force has been greatly improved, and then the advanced foreign technology introduced through international trade and foreign direct investment can be quickly digested, absorbed and efficiently applied by high-quality workers, which can greatly improve the country's or region's technological level and labor productivity, creating a catch-up effect, thus realizing the convergence of green growth. China's reform and opening-up practice over the past 40 years has fully proved this point. At the same time, knowledge is competitive and non-exclusive, and the knowledge and technology possessed by IHC will be diffused in the production process, so that other ordinary laborers can form and accumulate their own IHC through "learning by doing" and other means, which is beneficial to further improving the quality of labor.

(2) IHC impacts on technological progress. Nelson and Phelps pointed out that human capital has a technological innovation role [27]. At the same time, human capital is heterogeneous. IHC is the most innovative type of human capital, with scarce production allocation capacity and technological absorption and innovation capacity, as well as the ability to detect market disequilibrium and bring the market back to equilibrium. Compared with other types of human capital, workers with IHC usually have received higher education, mastered profound professional knowledge and cutting-edge technology, and are active in thinking, able to comprehensively utilize multidisciplinary knowledge to explore unknown fields. They are innovative talents, focusing on giving full play to the brain's intelligence, inspiration, intuition, will and other functions in the production process, and utilizing their strong innovative ability to promote technological upgrading and even realize disruptive technological innovation. Technological innovation increases the accumulation of knowledge stock in the R&D sector, which is applied to the production sector after being transformed by the innovation results, which not only enables other additional production factors such as capital and labor to maintain the incremental marginal returns, but also continuously creates new products. Through a Nielsen-Phelps type of mechanism, IHC is able to continuously produce new knowledge, new technologies and new products, which in turn drives green growth through technological progress and has a corresponding impact on growth convergence.

(3) IHC impacts through spatial spillovers. According to Schultz, human capital can be acquired through five types of investment: schooling, health care, on-the-job training, adult education and job migration. People migrate between regions in order to obtain, for example, higher job incomes or more room for development. From the perspective of stock, economically developed regions accumulate more IHC than economically less developed regions; at the same time, because economically developed regions have better infrastructure, working environment and living conditions, they also attract IHC from economically less developed regions to migrate here, a phenomenon known as the "siphon effect". Of course, the "siphon effect" of developed regions is not conducive to the realization of green growth convergence between the two types of regions. However, because of the long-term "siphon effect" caused by the developed regions of IHC in some areas of the formation of excessive concentration, the increasingly fierce competition between high-end talent, coupled with the developed regions of the increasingly crowded population, air pollution, prompting IHC from the developed regions to the less developed regions flow. This migration directly increases the stock of IHC in less developed regions, making the stock gaps of IHC between regions shrink, allowing the possibility of growth convergence between the two regions in green development to increase. In addition, the non-competitive and partially non-exclusive nature of knowledge and technology is prone to spatial spillover or diffusion, and green production

Table 1
Literature review on the relationship between human capital and ecological environment, growth convergence.

Author/s	Period	Region	Method	Variable	Empirical results
Literature review on the relationship between human capital and ecological environment					
Bano et al. (2018)	1971–2014	Pakistan	Autoregressive distributed lag model and the vector error correction model	Human capital, carbon emissions	Human capital can reduce carbon emissions in the long term
Z. Ahmed et al. (2020)	1970–2016	China	Bayer and Hack cointegration test and bootstrap causality technique	natural resources, human capital, urbanization, GDP, and ecological footprint	human capital mitigates environmental deterioration and has a moderating effect of promoting sustainable urbanization
Z. Ahmed et al. (2021)	1995–2017	Latin American and Caribbean countries	continuously-updated fully modified (CUP-BC) and continuously-updated bias-corrected (CUP-FM) long-run estimators et al.	information and communication technology, Human Capital, Globalization, Urbanization, CO2 Emissions	human capital adds to environmental degradation
Pata and Caglar (2021)	1980–2016	China	Augmented ARDL approach	income, human capital, globalization, renewable energy consumption, and trade openness	income, human capital, globalization, renewable energy consumption, and trade openness
M. Ahmad et al. (2022)	1984–2017	17 emerging countries	CS-ARDL	Financial development, environmental degradation and ecological footprint	human capital can reduce ecological footprint
Awan et al. (2024)	1971–2017	India	QARDL approach	Nuclear energy, human capital, urbanization and ecological footprint	human capital reduce ecological footprints
Tufail et al. (2024)	1990–2021	19 selected OECD economies	moment quantile regression	globalization, human capital, Green finance and green growth	human capital shows a significantly positive relationship with green growth
Literature review on the relationship between IHC and economic growth, ecological environment					
Xu and Li (2020)	2001–2013	China	spatial autoregressive regression model and spatial error model	IHC, Economic growth	IHC promotes economic growth
Wang and Wu (2020)	2003–2017	China and India	Panel data model	air pollution, technological IHC	Air pollution has a significant negative effect on the accumulation of technological innovative professionals
Lin et al. (2021)	2003–2017	China	ordinary least squares, and the system generalized method of moments	IHC, Economic Growth and CO2 Emissions	innovative human capital alleviates environmental deterioration
Wei Jin et al. (2022)	2003–2020	China	GTFP evaluation model, dynamic threshold model	environmental regulation, green total factor productivity and innovative human capital	IHC plays a threshold role
Yao et al. (2023)	2005–2018	China	panel regression models, mediation models, quantile regressions and threshold regressions	IHC on green total factor productivity	IHC are the driving force for GTFP growth
Literature review on the relationship between human capital and convergence					
Felice et al. (2012)	1891–2001	Italy	Panel model	human capital, social capital, value added	Human capital promotes growth convergence
Zhang et al. (2012)	1978–2009	China	standard deviation, coefficient of variation, Theil index	human capital, Per capita GDP	Human capital boosts growth convergence
Völlmecke et al. (2016)	2003–2010	EU	Endogenous broad capital model, Markov chain approach	FDI, human capital and income	Human capital is a determinant of convergence
Mannasoo et al. (2018)	2000–2013	European countries	Data envelopment analysis with the Malmquist productivity change index, GMM estimator	Human capital, R&D spending, GDP	Human capital promotes the convergence of emerging regions of Europe
Arcabic et al. (2021)	1990–2018	Asia-Pacific countries	metafrontier super epsilon based model (EBM)	Human Capital, trade competitiveness environmental efficiency	Human capital enhances environmental efficiency convergence
Appiah-Twum and Long (2023)	1917–2012	USA	Spatial panel mode, unit root tests, ordered probit estimation	Human capital, income	Human capital is the determinant of convergence

knowledge and technology developed by IHC in developed regions will diffuse through spatial spillover to less developed regions, thus driving green development in less developed regions.

3. Literature review and hypotheses development

IHC is a specific type derived from human capital, which also contains the basic attributes of human capital. IHC is the part of human capital that has a strong capacity and willingness to innovate and to solve problems in unconventional and productive ways, shifting the production possibilities frontier upwards and ultimately realizing increasing marginal returns [28,29].

Since the 1980s, the role of human capital on economic growth has been a research hotspot in the academic world, and in recent years, with the increasing deterioration of the earth's environment, the relationship between human capital (including IHC) and the ecological environment has gradually been emphasized by scholars in various countries. Novel research on such issues is presented in Table 1 in chronological order on the next page.

Many scholars have found in empirical studies that human capital favors the improvement of environmental quality [30–35]; however, there are also some scholars who have found in empirical studies that human capital exacerbates environmental degradation [36]. The reason for this is the result of ignoring the heterogeneity of human capital. IHC is a typical form of human capital heterogeneity, which is essentially a special kind of human capital [37]. In recent years, more and more scholars have begun to study the impact of IHC on economic growth and the ecological environment.

Xu and Li (2020) constructed a panel spatial econometric model based on the endogenous growth theory to empirically analyze the relationship between IHC and China's economic growth, and found that for every 1 % increase in the stock of IHC, the economic output can grow by 1.1038 % [38]. However, the traditional economic growth model has caused greater pollution to the human living environment. Two countries, China and India, have recently faced brain drain due to air pollution. Wang and Wu (2020) empirically examined the role of air pollution on the accumulation of technologically IHC by utilizing data from both China and India, and showed that a 1 % increase in PM2.5 concentration in Chinese cities resulted in a loss of approximately 146 technologically innovative professionals, while in Indian states, an increase of 1 % in PM_{10} concentration resulted in a 0.127 % decrease in the accumulation of technologically innovative professionals [39]. Although air pollution affects the accumulation of IHC, IHC can also counteract environmental pollution. Lin et al. (2021) empirically analyzed the impact of IHC on carbon dioxide emissions in economic growth using panel data from 30 provinces in China from 2003 to 2017, and found that IHC can significantly inhibit carbon dioxide emissions and effectively mitigate environmental degradation [40]. The environmentally friendly attributes of IHC have led scholars to link it with green development. Jin et al. (2022) argued that with the continuous growth of IHC in China in recent years, it is necessary to explore the intrinsic relationship between IHC, environmental regulation and green total factor productivity (GTFP) in depth, and found that there is a threshold effect of environmental regulation affecting green total factor productivity, and IHC is this threshold [41]. Yao et al. (2023), on the other hand, focuses directly on the relationship between graduate students, the most important carrier of IHC, and green total factor productivity, and finds that the expansion of graduate students in China has increased the accumulation of IHC, and that although the expansion of graduate students can directly improve regional GTFP to a certain extent, it also indirectly promotes GTFP through IHC, and the empirical results show that the mediating role of IHC accounts for 73 % [42]. From the findings of the above scholars, we can learn that IHC has a positive driving effect on regional GTFP.

In addition to this, can IHC also promote the convergence of green growth in different regions of China? With the emergence of new economic growth theories [43,44], the role of human capital on economic growth and convergence has received unprecedented attention. There are two main objects of analysis for scholars in various countries to study the issue of convergence of human capital on economic growth, one is different regions of the same country, and the other is the comparison between different countries. Felice (2012) characterizes human capital in terms of literacy, school enrollment, and the combination of the two in her study of regional convergence in Italy over a long period of time, 1891–2001, and the empirical tests show that human capital played an important role in economic growth in the first 50 years of the 20th century and favored growth convergence in the Northwest, Northeast, Central and South of Italy [45]. Zhang et al. (2012) empirically analyze the impact of human capital on growth convergence in the Beijing-Tianjin-Hebei region of China, and find that, after the introduction of the human capital variable characterized by the average years of schooling, the region exhibits strong conditional β-convergence over the period 1996–2009, suggesting that human capital is an important factor contributing to the convergence of the regional economy in the region [46]. Arcabic et al. (2021) empirically analyze the convergence of income inequality across U.S. states by employing a century-long data for the period 1917–2012, and find that human capital is the determinant of some states showing club convergence [47]. Among the comparative studies between different countries, Barro (1991) opened this area of research earlier and found through empirical tests that poor countries grow faster than rich countries only if human capital with a higher level of per capita income accumulates to a certain amount [48]. Cravo and Soukiazis (2008), with reference to Barro's approach Empirical studies have found that because different countries are at different stages of development, different levels of human capital produce different convergence effects, for example, advanced human capital, expressed as patent ratio or patent publication ratio, better explains the convergence process in the more developed OECD countries, while intermediate human capital, expressed as average years of schooling, better controls for the steady state in less developed countries [49]. Völlmecke et al. (2016) empirically analyzed the effect of FDI, human capital on the convergence of income levels expressed in terms of real GDP per capita using data from 269 regions of the European Union for the period 2030–2010 and found that human capital is a determinant of income convergence [50]. Mannasoo et al. (2018) empirically analyzed the contribution of human capital endowment to total factor productivity for 91 regions in 31 European countries over the period 2000–2013, using the share of the population aged 25–64 with tertiary education and the share of persons aged 25–64 who have participated in lifelong learning in the last four weeks as a measure of human capital, and the results of the test suggest that relative to the proximity to the production

frontier. The test results show that human capital in regions farther from the production frontier has a more positive impact on regional convergence trends than in regions closer to the production frontier [51]. Appiah-Twum and Long (2023) empirically analyzed the effects of green technology and human capital using panel data for Asia-Pacific countries from 1990 to 2018, and found that human capital can contribute to the convergence of these countries in terms of environmental efficiency [52].

From the conclusions of the above studies, it can be seen that human capital has a positive effect on the growth convergence of different regions or different countries in the same country; however, the above studies also have several obvious shortcomings: (1) The researchers ignore the impact of the spatial spillover effect of human capital on the growth convergence of different economic countries or areas; (2) homogenizing the human capital and ignoring the obvious heterogeneity of IHC which is part of it; (3) the study only tested the role of human capital stock without considering the impact of human capital quality. It is important to study and analyze the role of human capital quality on economic growth and gap reduction in various regions [53]. To address the shortcomings of existing studies, the main contributions of this paper are (1) to further analyze the impact of spatial spillover effects of human capital on the growth convergence of different economic entities from a spatial perspective; (2) to focus on the heterogeneity of human capital, and to target the role of IHC on the convergence of regional green growth; and (3) to study the role of IHC on the convergence of regional green growth, not only from the quantitative but also from the qualitative point of view.

4. Methodology

4.1. The construction of conditional β convergence model

The study of Qin and Yang (2017) pointed out that the convergence of economic development is one of the main bases for testing the coordinated development of regional economy [54], and similarly, for the convergence of green growth, it is one of the main bases for testing the coordinated development of regional green. Therefore, according to the convergence hypothesis of regional economic growth, this paper chooses the $\boldsymbol{\beta}$ convergence model to further examine the role of IHC development on regional green growth convergence. According to the neoclassical economic theory, the marginal returns of factors are decreasing, and thus the green growth of different regions or countries is convergent. Considering the spatial correlation between regions, the rate of convergence of green growth is slower than that in the neoclassical growth model [55]. If the spatial correlation effect is ignored, the setting of the convergence model will overestimate the role of IHC in promoting the convergence of green growth in China. The common spatial econometric models include the spatial autoregressive model (SAR model), the spatial error model (SEM model), and the spatial Durbin model (SDM model). In terms of transmission mechanisms, the SAR model assumes that the explained variable will exert an influence on other study units' explained variable through spatial interaction; the SEM model assumes that the knowledge or technological spatial spillover effect arises from the result of random shocks, and its spatial spillover effect mainly transmits through random error terms; the SDM model integrates the transmission mechanisms of the explained variable and random error spatial correlation, and also considers spatial interaction, believing that the level of green growth in a region is not only affected by its own independent variable, but also by the level of green growth in other regions and its own independent variable. The theoretical analysis of this paper shows that IHC can directly affect green growth, and it can also have an effect on green growth by affecting technological progress, and there is a spatial spillover effect of IHC affecting green growth, that is, the spatial attributes of independent variable IHC need to be considered in the setting of the model, and it is advisable to establish a spatial Doberman model. Based on this, this paper establishes the following convergence model based on the spatial Durbin model:

$$log\left(\frac{y_{it}}{y_{it-1}}\right) = C + \beta lny_{it-1} + \rho Wlog\left(\frac{y_{it}}{y_{it-1}}\right) + \gamma W \times lny_{it-1} + \theta IHC_{it} + \phi W \times IHC_{it} + \mu_{it} \tag{3}$$

in equation (3), y is the level of regional green growth; W is the spatial weight, using queen neighbor weights and geographic distance weights; IHC is the level of IHC in the region, including both quantitative and qualitative components; if $\boldsymbol{\beta}$ is significantly negative, it indicates that there is conditional convergence of regional green growth, and vice versa. If $\boldsymbol{\theta}$ is significantly positive, it indicates that the increase of IHC level has a positive effect on the enhancement of regional green growth rate, and vice versa; if $\boldsymbol{\phi}$ is significantly positive, it indicates that the neighboring regions have conditional convergence characteristics, and vice versa is divergence.$\boldsymbol{\phi}$ significantly positive, it indicates that the increase in the level of IHC in the neighboring areas has a positive effect on the enhancement of the local green growth rate, and vice versa. It is not difficult to find that whether θ and ϕ are significant or not in model (3) can only reflect the influence of IHC and its spatial function on regional green growth, but it is difficult to directly reflect the effect of IHC on the convergence of regional green growth, in this regard, some scholars use the comparison of absolute $\boldsymbol{\beta}$ convergence model and the conditional convergence model with core variables or the convergence speeds of the two to analyze and study [56]. Drawing on this idea, there are many factors affecting the green growth of a region, this paper selected foreign direct investment (*FDI*), industrial structure (*IND_S*), the degree of marketization (*M*) as control variables, the following spatial convergence model is constructed:

$$log\left(\frac{y_{it}}{y_{it-1}}\right) = C + \beta lny_{it-1} + \rho Wlog\left(\frac{y_{it}}{y_{it-1}}\right) + \gamma W \times lny_{it-1} + \phi_1 lnFDI + \phi_2 IND_S + \phi_3 MD + \phi_1 W \times lnFDI + \phi_2 W \times IND_S + \phi_3 W \times MD + \mu_{it} \tag{4}$$

The control variables of foreign direct investment, industrial structure and degree of marketization are specifically measured by the amount of actual foreign investment, the share of industrial added value in GDP and the marketization index, respectively.

Next, in order to analyze the impact of IHC on regional green convergence, IHC variable are added to model (4):

$$log\left(\frac{y_{it}}{y_{it-1}}\right) = C + \beta lny_{it-1} + \rho Wlog\left(\frac{y_{it}}{y_{it-1}}\right) + \gamma W \times lny_{it-1} + \theta IHC_{it} + \phi W \times IHC_{it} + \phi_1 lnFDI + \phi_2 IND\_S + \phi_3 MD + \phi_1 W \times lnFDI + \phi_2 W \times IND_S + \phi_3 W \times MD + \mu_{it} \quad (5)$$

Comparing the speed of convergence and convergence of model (5) and model (4), if the speed of convergence of model (5) is larger while the speed of convergence of model (4) is smaller, or the estimation results of model (5) show convergence, while the estimation results of model (4) show that the regional green growth does not converge, then it means that the incorporation of IHC elements makes the model show convergence, IHC has a convergent effect on regional green growth.

4.2. Club convergence

Club convergence is a common pattern of convergence that is prevalent in the growth process of economies around the globe. However, only regions with similar economic structure characteristics and closer initial states will eventually converge to the same steady state. In terms of the club convergence characteristics of China's economic growth, relevant studies have shown that there are three convergence clubs in the east, center and west [57], and there is also a "double-peak convergence" between the east and the center and west [58,59]. The eastern region has a clear advantage in IHC and green growth over the central and western regions, while the accumulation of IHC in the central region is higher than that in the western region. However, in terms of internal structure, the economic growth of Hubei, Henan and Shanxi in the central region is more dependent on industry, while the production capacity of Gansu, Qinghai and Ningxia in the western region is lagging behind, and thus the central and western regions have a relatively similar internal structure. Therefore, this paper will follow the division of east and central and west to club convergence analysis.

It should be emphasized that for club convergence, some studies have designed empirical analysis models by adding regional dummy variables on the basis of β convergence model, but this is often considered in the case of absolute β convergence. In this paper, the analysis of club convergence is carried out by group regression, that is, the sample is divided into the East and the Midwest to carry out regression analysis respectively, using equations (4) and (5) as the specific model form.

4.3. Variable descriptions

Model (5) contains the explained variable y meaning regional green growth level, the explanatory variable IHC meaning regional IHC level, and three control variables, i.e., foreign direct investment, industrial structure, and degree of marketization.

4.3.1. The explained variable

The level of green growth is the explained variable of the empirical study in this paper, which is denoted by y. Cao et al. (2022) pointed out that green growth takes into account the balance and coordination of multiple systems, such as the environment, the economy, and the society, which is conducive to the environmental protection and ecological civilization, and is able to achieve the sustainable development of human beings [60]. In this paper, on the basis of previous studies [61,62], we constructed a green growth index evaluation system that includes the following systems:

The evaluation index system of green growth level contains a number of variables for evaluation, among which GDP per capita, natural population growth rate, tertiary industry's share of GDP, investment in fixed assets of the whole society, electricity consumption per unit of GDP, the number of beds in medical institutions per 10,000 people, green space per capita in the city, investment in industrial pollution control, the area of forest pest prevention and control, area of planted forests in the current year, and the industrial output value's share of GDP are obtained from the China Statistical Yearbook. The data of such indicators as per capita water resources, the number of nature reserves, the area covered by forests and the amount of coal savings were obtained from the China Energy Statistical Yearbook; the data of such indicators as the rate of disposal of pollution-free domestic garbage, carbon dioxide emissions, chemical oxygen demand emissions and wastewater emissions were obtained from the China Statistical Yearbook on Environment; The data for indicators such as the proportion of R&D expenditures in government financial expenditures were obtained from the China Statistical Yearbook on Science and Technology. Some of the missing data for individual provinces in the above indicators were filled in by consulting the statistical yearbooks of each province, city, and autonomous prefecture. Considering the availability and continuity of data, this paper takes the data of 30 provinces, municipalities and autonomous prefectures from 2004 to 2018 as the research samples (Tibet is excluded due to the seriousness of missing data). Among them, the investment in fixed assets of the whole society was calculated using the perpetual inventory method [63] with the year of 2000 as the base period. Drawing on the study of Zhang Jun and Zhang Yuan; the GDP per capita was also converted to the real value using 2000 as the base period.

This paper adopts the vertical and horizontal widening gap method, which is capable of comprehensive evaluation based on panel data, to measure and analyze the level of green development in each region. The results of the weights of each index measured by this paper using this method are shown in the rightmost column in Table 1. The specific formula for calculating the green growth level index of each province, city and autonomous prefecture is as follows:

$$I_{it} = \sum_{s=1}^{q} o_s \sum_{it}^{m} r_{ijt} \times \omega_j \quad (6)$$

in equation (6), $I_{it} \in [0,1]$, The larger the value of I_{it}, the higher the level of green growth; q represents the number of sub-indexes; m represents the number of base indexes; O_s represents the weight of the first s weight of the sub-index. $\sum_{s=1}^{q} o_s = 1$; ω_j is the weight of the jth basic index; $\sum_{it}^{k} \omega_j = 1$; r_{ijt} represents the index value of the jth basic index in the s sub-index after standardization in the t year. Using the above methodology to measure the level of green growth in China's provincial-level regions from 2004 to 2018, and further calculating its national average, the results are shown in Fig. 1.

4.3.2. The explanatory variable

IHC (denoted by IHC) is the core explanatory variable of this study, including two dimensions of innovative human capital quantity (denoted by IHCA) and innovative human capital quality (denoted by IHCQ). Based on the different methods used by scholars around the world to measure the quantity of human capital and the quantity of IHC [41,42,64], this paper adopts the level of education to measure the quantity of IHC in China's whole society, and considers laborers with tertiary education as IHC. The quantity of IHC is calculated by dividing the workers with higher education into three levels: college, undergraduate, and postgraduate (including master's and doctoral postgraduates), which correspond to 15, 16, and 21 years of education, and then multiplying the number of employed people in the three levels by the corresponding number of years of education and summing them up to get the quantity of IHC in the whole country or in a certain province. For the quality of IHC, this paper refers to different methods used by scholars of various countries to measure the quality of human capital [53,65,66], and uses the indicators of the number of scientific and technological papers published per 10,000 employed persons with higher education and the number of patents authorizations as an indicator to measure the quality of IHC in China's society as a whole. According to the empirical practice of converting scientific and technical papers to granted patents in Chinese research institutes and universities, the conversion coefficient between scientific and technical papers and granted patents is 1:1, which can be used to test the quality of all IHC in the country or in a province. The quantity and quality of IHC in China are measured by using the above methods, as shown in Fig. 2. It is not difficult to find that the quantity and quality of IHC in China are increasing obviously, and both of them have shown a rapid growth rate after 2011.

4.3.3. Control variables

The control variables in the convergence model include foreign direct investment (FDI), industrial structure (IND_S), and marketization degree (MD). FDI, industrial structure and marketization degree are specifically measured by the amount of actual foreign investment, the share of industrial added value in GDP and the marketization index [67], respectively. The data for FDI were obtained from the China Trade and External Economics Statistical Yearbook. The data of the industrial added value were obtained from the China Statistical Yearbook.

5. Results

The model set up in this research paper is a panel spatial econometric model, and the spatial correlation of the variables needs to be tested first before the estimation of the empirical model. The results of calculating Moran's I and the corresponding statistics show that there is a significant spatial correlation between both the explained variables and the core explanatory variables. The design of this paper based on spatial panel econometric model for empirical research is reasonable and can be analyzed for subsequent research.

5.1. Conditional β-convergence analysis

Models (4) and (5) were estimated under two weights, firstly, the effect of the quantity of IHC on the convergence of green growth was analyzed, and the results of Hausman's test showed that the model estimation was better under the fixed effect; therefore, the model was estimated under the fixed effect, and the results are shown in Table 3.

The estimation results of the model in Table 2 show that the estimated coefficients of the parameter β are −0.2552 and −0.2306 for the inclusion and exclusion of the quantity of IHC under the distance weights, which are both significant at the 1%nlevel, and the corresponding rates of convergence of green growth are 0.2946 and 0.2621, respectively, suggesting that the quantity of IHC in China can significantly contribute to the regional green growth convergence. The coefficients of the spatial lag term of the IHCA, W × IHCA, are both significant at the 1 % level under the distance weights and the neighboring weights is negative, that is, the spatial spillover effect of the quantity of IHC in China has a significant effect on regional green growth convergence, but the effect is manifested as a

Fig. 1. The changing trend of Green growth level in China from 2004 to 2018.

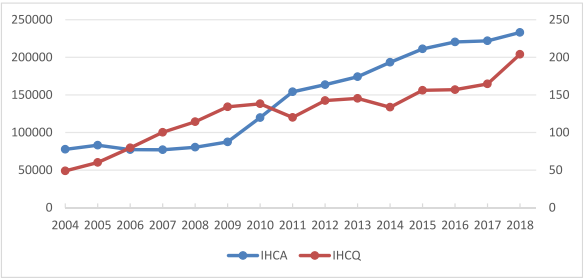

Fig. 2. The changing trend of IHCA and IHCQ in China from 2004 to 2018.

Table 2
System of indicators for evaluating the level of green growth.

System layer	Index layer	Sources	Weights	Index attribute
Socio-economic system	GDP per capita	China Statistical Yearbook	0.0294	Positive
	natural population growth rate		0.0605	
	The percentage of tertiary industry in GDP		0.0403	
	Investment in fixed assets of the whole society		0.0391	
Ecological environment	Sulfur dioxide emissions	China Statistical Yearbook on Environment	0.0162	Negative
	Chemical oxygen demand emissions		0.0267	
	Wastewater discharge		0.0608	
	Electricity consumption per unit of GDP		0.0089	
Natural assets	Per capita water resources	China Energy Statistical Yearbook	0.1084	Positive
	Number of nature reserves		0.0406	
	Forest coverage		0.0727	
	Coal storage		0.0264	
Quality of life	Pollution-free treatment rate of domestic waste	China Statistical Yearbook	0.0267	Positive
	Number of beds in medical institutions per 10,000 people		0.0194	
	Internet penetration rate		0.0201	
	Urban per capita green area		0.0265	
Policy Support	Proportion of R&D expenditure in government financial expenditure	China Statistical Yearbook on Science and Technology	0.089	Positive
	Investment in industrial pollution control	China Statistical Yearbook	0.0876	
	Forest pest control area		0.0948	
	Afforestation area of the year		0.1059	

negative spatial spillover effect that inhibits green growth convergence; it can be found that the rate of green growth convergence is larger when the quantity of IHC is included, and that convergence is significant, indicating that IHC and its spatial effect have a positive effect on green growth convergence that has a significant green growth convergence effect. Under neighborhood weights, the model estimation results also conclude that the quantity of IHC can significantly promote the convergence of regional green growth and the speed of convergence is 0.3772. At the same time, it can be found that the speed of green growth convergence under neighborhood weights is significantly larger than the speed of green growth convergence under distance weights, which suggests that when the spatial correlation of green growth that decays with distance is taken into account, the speed of green growth will be slowed down.

Next, the paper further analyzes the impact of IHCQ on green growth convergence. The model (5) and model (4) with and without the inclusion of IHCQ are estimated under distance weights and neighborhood weights, respectively, and the results of Hausman's test similarly show that the model estimation under fixed effects is better. Therefore, the models were estimated under fixed effects and the results are shown in Table 4.

The results in Table 4 show that the estimated coefficients of the parameter β are negative and significant at the 1 % level in both the models that include and do not include IHCQ, indicating that IHCQ significantly contributes to regional green growth convergence, suggesting that there is a significant conditional β-convergence effect on green growth in China; the coefficient of the spatial lag term of IHCQ, W × IHCQ, is not significant, indicating that the spatial effect of IHCQ does not present a significant promotion effect on regional green growth. In addition, whether under distance weights or neighborhood weights, green growth shows a greater rate of convergence in the model that incorporates IHCQ ($0.2644 > 0.2621$; $0.3426 > 0.3395$), indicating that IHCQ and its spatial effect have a positive effect on regional green growth convergence and that IHCQ has a significant green growth convergence effect. Similarly, the speed of green growth convergence under distance weights is smaller than that of neighbor weights, and the inclusion of complex spatial correlations of green growth will reduce the speed of green growth convergence.

Table 3
The estimated results of the green growth convergence effect model for IHCA.

Variables	W_{ij}^{d}		W_{ij}^{0-1}	
	(1)	(2)	(3)	(4)
lny_{it-1}	−0.2552*** (0.0347)	−0.2306*** (0.0349)	−0.3142*** (0.0361)	−0.2879*** (0.0368)
IHCA	0.0341*** (0.0092)	/	0.0346*** (0.0089)	/
INDS	−0.0003 (0.0005)	−0.0004 (0.0005)	−0.0006 (0.0005)	−0.0007 (0.0005)
Ln FDI	0.0014 (0.0027)	0.0010 (0.0028)	0.0007 (0.0026)	0.0013 (0.0026)
MD	−0.0003 (0.0031)	0.0003 (0.0033)	0.0012 (0.0032)	0.0005 (0.0034)
$W\times$ lny_{it-1}	0.1229** (0.0575)	0.0942* (0.0578)	0.1883*** (0.0448)	0.1577*** (0.0459)
$W\times$ *IHCA*	−0.1032*** (0.0252)	/	−0.0535*** (0.0117)	/
$W\times$ *INDS*	−0.0052*** (0.0015)	−0.0028** (0.0013)	−0.0028** (0.0009)	−0.0019** (0.0009)
$W\times$ *Ln FDI*	0.0306*** (0.0091)	0.0096* (0.0055)	0.0191*** (0.0048)	0.0123*** (0.0040)
$W\times$ *MD*	0.0008 (0.0042)	−0.0022 (0.0042)	−0.0002 (0.0038)	−0.0012 (0.0039)
ρ	0.7472*** (0.0444)	0.7782*** (0.1020)	0.6368*** (0.0358)	0.6318*** (0.0364)
sigma_e	0.0007*** (0.0001)	0.0007*** (0.0001)	0.0007*** (0.0001)	0.0007*** (0.0001)
log − likehood	922.877	911.310	906.544	893.278
Hausman test p-value	0.0000	0.0016	0.0000	0.0000
R^2	0.3010	0.2444	0.15535	0.6596
Convergence rate	0.2946	0.2621	0.3772	0.3395
Observed number	420	420	420	420

Note: y means the level of regional green growth; IHCA means the quantity of IHC; INDS means industrial structure; FDI means foreign direct investment; MD means marketization degree; "*", "**", and "***" indicate significance at the 10 %, 5 %, and 1 % levels, respectively. Standard errors are in parentheses.

Table 4
The estimated green growth convergence effect model of IHCQ.

Variables	W_{ij}^{d}		W_{ij}^{0-1}	
	(1)	(2)	(3)	(4)
lny_{it-1}	−0.2323*** (0.0351)	−0.2306*** (0.0349)	−0.2901*** (0.0368)	−0.2879*** (0.0368)
IHCQ	0.0032 (0.0272)	/	0.0179 (0.0274)	/
INDS	−0.0004 (0.0005)	−0.0004 (0.0005)	−0.0007 (0.0005)	−0.0007 (0.0005)
Ln FDI	0.0009 (0.0028)	0.0010 (0.0028)	0.0013 (0.0026)	0.0013 (0.0026)
MD	0.0005 (0.0032)	0.0003 (0.0033)	−0.0008 (0.0033)	0.0005 (0.0034)
$W\times$ lny_{it-1}	0.0743* (0.0510)	0.0942* (0.0578)	0.1651*** (0.0476)	0.1577*** (0.0459)
$W\times$ *IHCQ*	0.1068 (0.0985)	/	−0.0449 (0.0616)	/
W × INDS	−0.0027** (0.0014)	−0.0028** (0.0013)	−0.0020** (0.0009)	−0.0019** (0.0009)
$W\times$ *Ln FDI*	0.0083 (0.0057)	0.0096* (0.0055)	0.0128*** (0.0041)	0.0123*** (0.0040)
$W\times$ *MD*	−0.0015 (0.0043)	−0.0022 (0.0042)	−0.0009 (0.0039)	−0.0012 (0.0039)
ρ	0.7642*** (0.0435)	0.7782*** (0.1020)	0.6348*** (0.0367)	0.6318*** (0.0364)
sigma_e	0.0007*** (0.0001)	0.0007*** (0.0001)	0.0007*** (0.0001)	0.0007*** (0.0001)
log − likehood	911.917	911.310	893.735	893.278
Hausman test p-value	0.0036	0.0016	0.0000	0.0000
R^2	0.2868	0.2444	0.15535	0.6596
Convergence rate	0.2644	0.2621	0.3426	0.3395
Observed number	420	420	420	420

Note: y means the level of regional green growth; IHCQ means the quality of IHC; INDS means industrial structure; FDI means foreign direct investment; MD means marketization degree; "*", "**", and "***" indicate significance at the 10 %, 5 %, and 1 % levels, respectively. Standard errors are in parentheses.

5.2. Club convergence analysis

The previous analysis shows that there is a significant conditional β convergence in green growth among provinces in China, and a further question to consider is whether the convergence of green growth exists within the two major regions of the East and the Midwest? Is there a club convergence phenomenon for green growth, i.e., does IHC drive club convergence in green growth? This paper will analyze this further.

Firstly, the eastern region is analyzed for the role of IHCA on the convergence of green growth, and since the Hausman test results all passed at the 1 % level, the fixed effects are chosen to estimate the model, and the results are shown in Table 5.

The results in Table 5 show that: the estimated coefficient of the first-order time lag of green growth in the eastern region is negative, and it is significant at the 1 % level, indicating that there is a significant conditional β convergence phenomenon in the eastern region's green growth. Including IHCA and its spatial lag term in the distance weight and adjacency weight will respectively promote the convergence speed of green growth by about 15.27 % and 22.09 %, driving the regional convergence of green growth. In the eastern region, IHCA has a significant green growth convergence effect.

Table 5
The estimated results of the green growth convergence effect model of IHCA. in the eastern region.

Variables	W_{ij}^{d}		W_{ij}^{0-1}	
	(1)	(2)	(3)	(4)
lny_{it-1}	−0.3633*** (0.0659)	−0.3240*** (0.0681)	−0.4189*** (0.0692)	−0.3589*** (0.0712)
IHCA	0.0209 (0.0157)	/	0.0287* (0.0152)	/
INDS	−0.0039** (0.0016)	−0.0027* (0.0016)	−0.0029* (0.0016)	−0.0025* (0.0015)
Ln FDI	0.0001 (0.0069)	0.0024 (0.0071)	0.0032 (0.0065)	0.0027 (0.0065)
MD	−0.0017 (0.0057)	−0.0003 (0.0059)	0.0049 (0.0058)	0.0055 (0.0060)
$W\times$ lny_{it-1}	−0.0703 (0.1311)	−0.0594* (0.0578)	0.1307 (0.0893)	0.0363 (0.0905)
$W\times$ *IHCA*	−0.1352*** (0.0343)	/	−0.0597*** (0.0186)	/
W × INDS	−0.0145*** (0.0043)	−0.0072** (0.0033)	−0.0075** (0.0028)	−0.0062** (0.0025)
$W\times$ *Ln FDI*	0.0236 (0.0158)	0.0014 (0.0152)	0.0033 (0.0100)	−0.0025 (0.0101)
$W\times$ *MD*	0.0018 (0.0069)	−0.0055 (0.0073)	−0.0104 (0.0065)	−0.0119* (0.0069)
ρ	0.4761*** (0.0903)	0.5396*** (0.0821)	0.5067*** (0.0358)	0.4770*** (0.0627)
sigma_e	0.0011*** (0.0001)	0.0012*** (0.0001)	0.0010*** (0.0001)	0.0011*** (0.0001)
$log-likehood$	303.121	294.490	301.593	294.393
Hausman test p-value	0.0000	0.0064	0.0008	0.0002
R^2	0.1334	0.1406	0.1395	0.1418
Convergence rate	0.4515	0.3917	0.5428	0.4446
Observed number	154	154	154	154

Note: y means the level of regional green growth; IHCA means the quantity of IHC; INDS means industrial structure; FDI means foreign direct investment; MD means marketization degree; "*", "**", and "***" indicate significance at the 10 %, 5 %, and 1 % levels, respectively. Standard errors are in parentheses.

Secondly, the paper analyzes the role of IHCQ in promoting green convergence in the East China region. The Hausman test shows that the fixed-effect model is more suitable at the 5 % and 1 % levels of significance. The fixed effects are still chosen to estimate the model, and the results are shown in Table 6.

The results in Table 6 show that: First, the estimated coefficients of the first-order time lag term of green growth are all negative and are significant at 1 % level, which also indicates the existence of conditional β convergence of green growth in the eastern region; second, under distance weights and neighborhood weights, adding IHCQ increases the rate of green growth convergence by about 2.66 % and about 2.25 %, respectively, and there is a clear green growth convergence effect of IHCQ in the eastern region. Comparison of the effects of IHCA and IHCQ on green growth convergence in the eastern region reveals that IHCA enhances the intensity of the green growth convergence rate more, which is related to the fact that the eastern region's own economic level is higher, and the development of green technology is more difficult, so that IHCQ can play a role only in the green technological innovation, while IHCA can play a role in both green awareness and green innovation. In addition, the spatial lag term of IHCQ has a significantly negative effect on green growth, which is the same as that of the national estimation, due to the existence of the "siphon effect", the accumulation of IHCA in the neighboring regions is conducive to the economic growth and green innovation of the eastern region.

Next, the impact of IHCA in the Midwest region on the convergence of green growth is analyzed, and the results of Hausman's test

Table 6
The estimated results of the green growth convergence effect model of IHCQ in the eastern region.

Variables	W_{ij}^{d}		W_{ij}^{0-1}	
	(1)	(2)	(3)	(4)
lny_{it-1}	−0.3310*** (0.0683)	−0.3240*** (0.0681)	−0.3653*** (0.0713)	−0.3589*** (0.0712)
IHCQ	0.0259 (0.0377)	/	0.0255 (0.0364)	/
INDS	−0.0027* (0.0016)	−0.0027* (0.0016)	−0.0026* (0.0016)	−0.0025* (0.0015)
Ln FDI	0.0030 (0.0070)	0.0024 (0.0071)	0.0030 (0.0066)	0.0027 (0.0065)
MD	−0.0001 (0.0060)	−0.0003 (0.0059)	0.0044 (0.0062)	0.0055 (0.0060)
$W\times$ lny_{it-1}	−0.1116 (0.1373)	−0.0594* (0.0578)	0.0439 (0.0921)	0.0363 (0.0905)
$W\times$ *IHCQ*	0.1163 (0.0927)	/	−0.0343 (0.0659)	/
W × INDS	−0.0079** (0.0034)	−0.0072** (0.0033)	−0.0062** (0.0025)	−0.0062** (0.0025)
$W\times$ *Ln FDI*	−0.0029 (0.0155)	0.0014 (0.0152)	−0.0024 (0.0103)	−0.0025 (0.0101)
$W\times$ *MD*	−0.0041 (0.0074)	−0.0055 (0.0073)	−0.0109 (0.0007)	−0.0119* (0.0069)
ρ	0.5065*** (0.0881)	0.5396*** (0.0821)	0.4779*** (0.0629)	0.4770*** (0.0627)
sigma_e	0.0012*** (0.0903)	0.0012*** (0.0001)	0.0011*** (0.0001)	0.0011*** (0.0001)
$log-likehood$	295.445	294.490	294.789	294.393
Hausman test p-value	0.0116	0.0064	0.0002	0.0002
R^2	0.1755	0.1406	0.1387	0.1418
Convergence rate	0.4020	0.3916	0.4546	0.4446
Observed number	154	154	154	154

Note: y means the level of regional green growth; IHCQ means the quality of IHC; INDS means industrial structure; FDI means foreign direct investment; MD means marketization degree; "*", "**", and "***" indicate significance at the 10 %, 5 %, and 1 % levels, respectively. Standard errors are in parentheses.

show that the model that does not incorporate IHCA under the distance weights has better estimation results under the random effect, and all other models have better estimation results under the fixed effect. On this basis, the models are estimated and the results are shown in Table 6.

Analyzing the results in Tables 6 and it can be seen that, first, the first-order lag term coefficient of green growth is significantly negative at the level of 1 %, indicating the existence of conditional β convergence of green growth in the Midwest region; second, the inclusion of IHCA under distance weighting and neighborhood weighting raises the rate of green growth convergence by 90.49 % and 7.08 %, respectively, and that the rate of green growth convergence decreases after considering the spatial correlation relationship under complex distance decay. Comparing the speed of green growth convergence between the east and the Midwest region, the speed in the east is faster; however, further comparing the relative roles of IHCA in the two regions, we can find that the average effect of IHCA on the convergence rate of green growth in the eastern region is 18.68 % (the average value of distance weight and adjacency weight), and the average effect of IHCA in the Midwest region on the convergence of green growth is 48.75 %, which is significantly higher than that in the eastern region. The intrinsic reason for this is that IHCA in the eastern region is less significant in increasing the rate of green growth (see Table 4), while IHCA in the Midwest region has a significant effect on the increase in the rate of green growth at the 1 % level. Therefore, although the eastern region has a higher IHCA and a higher level of green growth, the average effect of IHCA on the convergence speed of green growth is weaker. However, the lower level of green growth and less IHC in the Midwest region leave more space for increasing IHCA to drive green growth and the convergence of green growth.

Finally, the green growth convergence effect of IHCQ in the Midwest region is analyzed. The results of Hausman's test show that the estimation results of all models are better under random effects. Therefore, the model (5) and model (4) with and without the inclusion of IHCQ are estimated under random effects with the Midwest region as the samples, and the results are shown in Table 7 (see Table 8).

From the results in Tables 7 and it can be found that the inclusion of IHCQ variable under distance weights and neighborhood weights increases the speed of green growth convergence by 4.48 % and 5.60 %, respectively, and that IHCQ in the Midwest region has a significant green growth convergence effect. Similarly, comparing the role of IHCQ in green growth in the eastern and the Midwest region, the average effect of IHCQ on the improvement of green growth convergence rate in the eastern is 2.46 %, and the average effect of IHC on the improvement of green growth convergence rate in the Midwest region is 5.04 %, which is significantly higher than that of the eastern, which is consistent with the fact that the quality of human capital in the Midwest region not only plays a significant role in local green growth, but also has a significant spatial spillover effect (in the Midwest region, the variable *IHCQ* and its spatial lag term W × *IHCQ* are both significantly positive in the model).

5.3. Robustness test

From the point of view of the model, this paper uses adjacency weight and distance weight for empirical analysis, and the conclusions of the model under the two kinds of weights are basically the same, which proves the robustness of the research model to a certain extent.

From the sample perspective, if the model and the estimation results are robust, a small amount of sample changes will not form a fatal impact on the estimation results of the model. From the spatial dimension, the article conducted empirical studies at the national level and regional levels such as the East and the Midwest, respectively, and all of them show that IHC has a facilitating effect on the convergence of green growth, which also proves the robustness of the research model to a certain extent. From the temporal dimension,

Table 7
The estimated results of the green growth convergence effect model of IHCA in the Midwest region.

Variables	W_{ij}^{d}		W_{ij}^{0-1}	
	(1)	(2)	(3)	(4)
lny_{it-1}	−0.2153*** (0.0401)	−0.1195*** (0.0220)	−0.2758*** (0.0423)	−0.2671*** (0.0712)
IHCA	0.0513*** (0.0153)	/	0.0409*** (0.0159)	/
INDS	−0.0005 (0.0005)	−0.0004 (0.0003)	−0.0008 (0.0005)	−0.0008 (0.0005)
Ln FDI	−0.0002 (0.0029)	0.0018 (0.0016)	−0.0006 (0.0031)	0.0013 (0.0028)
MD	−0.0003 (0.0038)	0.0004 (0.0019)	−0.0067 (0.0042)	−0.0070 (0.0043)
$W\times\ lny_{it-1}$	0.1166** (0.0584)	−0.0037 (0.0421)	0.1498*** (0.0505)	0.1206** (0.0496)
$W\times\ IHCA$	−0.1020*** (0.0328)	/	−0.0684*** (0.0227)	/
W × INDS	−0.0030** (0.0012)	−0.0026** (0.0010)	−0.0026*** (0.0008)	−0.0025*** (0.0009)
$W\times\ Ln\ FDI$	0.0237*** (0.0087)	0.0116** (0.0045)	0.0235*** (0.0054)	0.0164*** (0.0043)
$W\times\ MD$	0.0009 (0.0051)	−0.0013 (0.0036)	0.0080 (0.0050)	0.0074 (0.0050)
ρ	0.7586*** (0.0444)	0.7573*** (0.0439)	0.6044*** (0.0436)	0.6007*** (0.0443)
sigma_e	0.0005*** (0.0000)	0.0006*** (0.0000)	0.0006*** (0.0000)	0.0006*** (0.0001)
$log-likehood$	620.056	606.912	603.089	597.454
Hausman test p-value	0.0152	0.2640	0.0004	0.0025
R^2	0.3339	0.3381	0.1919	0.2090
Convergence rate	0.2425	0.1273	0.3327	0.3107
Observed number	266	266	266	266

Note: y means the level of regional green growth; IHCA means the quantity of IHC; INDS means industrial structure; FDI means foreign direct investment; MD means marketization degree; "*", "**", and "***" indicate significance at the 10 %, 5 %, and 1 % levels, respectively. Standard errors are in parentheses.

Table 8
The estimated results of the green growth convergence effect model for IHCQ. in the Midwest region.

Variables	W_{ij}^{d}		W_{ij}^{0-1}	
	(1)	(2)	(3)	(4)
lny_{it-1}	−0.1245*** (0.0228)	−0.1195*** (0.0220)	−0.2797*** (0.0433)	−0.2671*** (0.0712)
IHCQ	0.0567** (0.0203)	/	0.0598** (0.0297)	/
INDS	−0.0004 (0.0003)	−0.0004 (0.0003)	−0.0007 (0.0005)	−0.0008 (0.0005)
Ln FDI	−0.0016 (0.0016)	0.0018 (0.0016)	−0.0011 (0.0029)	0.0013 (0.0028)
MD	−0.0001 (0.0022)	0.0004 (0.0019)	−0.0054 (0.0044)	−0.0070 (0.0043)
$W\times$ lny_{it-1}	−0.0523 (0.0517)	−0.0037 (0.0421)	0.1716 (0.0505)	0.1206** (0.0496)
$W\times$ *IHCQ*	0.2941* (0.01855)	/	0.4212*** (0.01543)	/
W × INDS	−0.0024** (0.0010)	−0.0026** (0.0010)	−0.0026*** (0.0009)	−0.0025*** (0.0009)
$W\times$ *Ln FDI*	0.0095** (0.0048)	0.0116** (0.0045)	0.0133*** (0.0044)	0.0164*** (0.0043)
$W\times$ *MD*	−0.0011 (0.0038)	−0.0013 (0.0036)	0.0043 (0.0051)	0.0074 (0.0050)
ρ	0.7265*** (0.0498)	0.7573*** (0.0439)	0.5622*** (0.04792)	0.6007*** (0.0443)
sigma_e	0.0006*** (0.0001)	0.0006*** (0.0000)	0.0006*** (0.0001)	0.0006*** (0.0001)
$log-likehood$	608.487	606.912	601.241	597.454
Hausman test p-value	0.2345	0.2640	0.0043	0.0025
R^2	0.4105	0.3381	0.2952	0.2090
Convergence rate	0.1330	0.1273	0.3281	0.3107
Observed number	266	266	266	266

Note: y means the level of regional green growth; IHCQ means the quality of IHC; INDS means industrial structure; FDI means foreign direct investment; MD means marketization degree; "*", "**", and "***" indicate significance at the 10 %, 5 %, and 1 % levels, respectively. Standard errors are in parentheses.

based on the research by Liu and Wang (2018) [68], the basic model was estimated by excluding the data from 2004 to 2018 in the sample, as shown in Table 9 and Table 10. It is not difficult to find that the above conclusion on the convergence of green growth driven by IHC still holds true, indicating that the model studied in this paper is robust.

Additionally, the endogeneity problem of the model is also an issue that cannot be ignored. There may be a bidirectional causal relationship between IHC and green growth, which in turn may cause bias in the estimation of the model. For this reason, it is necessary to select appropriate instrumental variables to test the robustness of the model. Kelejian et al. (2004) showed that $\left(WX, W^2X, \ldots, W^nX\right)$ are theoretically ideal instruments [69], so we follow the research of Yu and Liu (2013) [70] and choose W × IHCA and W × IHCQ as

Table 9
Robustness test results of the green growth convergence effect model of IHCA.

Variables	W_{ij}^{d}		W_{ij}^{0-1}	
	(1)	(2)	(3)	(4)
lny_{it-1}	−0.2491*** (0.0426)	−0.2343*** (0.0429)	−0.3054*** (0.0454)	−0.2991*** (0.0460)
IHCA	0.0279*** (0.0105)	/	0.0242** (0.0104)	/
INDS	−0.0002 (0.0006)	−0.0002 (0.0006)	−0.0006 (0.0006)	−0.0006 (0.0005)
Ln FDI	0.0003 (0.0034)	0.0006 (0.0035)	0.0013 (0.0034)	0.0020 (0.0034)
MD	−0.0006 (0.0036)	0.0002 (0.0036)	0.0004 (0.0038)	0.0012 (0.0038)
$W\times$ lny_{it-1}	0.1288* (0.0705)	0.0932* (0.0604)	0.1835*** (0.0553)	0.1696*** (0.0557)
$W\times$ *IHCA*	−0.0872*** (0.0300)	/	−0.0385*** (0.0136)	/
W × INDS	−0.0052*** (0.0017)	−0.0036** (0.0016)	−0.0032** (0.0011)	−0.0027** (0.0010)
$W\times$ *Ln FDI*	0.0260** (0.0122)	0.0055 (0.0070)	0.0152** (0.0063)	0.0109** (0.0052)
$W\times$ *MD*	0.0007 (0.0049)	−0.0030 (0.0047)	−0.0018 (0.0043)	−0.0032 (0.0044)
ρ	0.7595*** (0.0476)	0.7758*** (0.1020)	0.6366*** (0.0395)	0.6371*** (0.0394)
sigma_e	0.0007*** (0.0001)	0.0007*** (0.0001)	0.0007*** (0.0001)	0.0007*** (0.0001)
$log-likehood$	784.378	778.343	770.499	765.363
Hausman test p-value	0.0051	0.0139	0.0007	0.0002
R^2	0.3018	0.2373	0.1598	0.1313
Convergence rate	0.2865	0.2668	0.3644	0.3554
Observed number	360	360	360	360

Note: y means the level of regional green growth; IHCA means the quantity of innovative human capital; INDS means industrial structure; FDI means foreign direct investment; MD means marketization degree; "*", "**", and "***" indicate significance at the 10 %, 5 %, and 1 % levels, respectively. Standard errors are in parentheses.

Table 10
Robustness test results of the green growth convergence effect model of IHCQ.

Variables	W_{ij}^{d}		W_{ij}^{0-1}	
	(1)	(2)	(3)	(4)
lny_{it-1}	−0.2359*** (0.0429)	−0.2343*** (0.0429)	−0.2990*** (0.0460)	−0.2991*** (0.0460)
IHCQ	0.0117 (0.0291)	/	0.0011 (0.0293)	/
INDS	−0.0002 (0.0006)	−0.0002 (0.0006)	−0.0006 (0.0005)	−0.0006 (0.0005)
Ln FDI	0.0008 (0.0035)	0.0007 (0.0035)	0.0020 (0.0034)	0.0020 (0.0034)
MD	0.0004 (0.0037)	0.0002 (0.0037)	0.0013 (0.0038)	0.0012 (0.0038)
$W\times$ lny_{it-1}	0.0936* (0.0606)	0.0932* (0.0604)	0.1690*** (0.0564)	0.1696*** (0.0557)
$W\times$ *IHCQ*	0.1356 (0.1364)	/	0.0062 (0.0750)	/
W × INDS	−0.0032* (0.0016)	−0.0036** (0.0016)	−0.0027** (0.0011)	−0.0027** (0.0010)
$W\times$ *Ln FDI*	0.0042 (0.0072)	0.0055 (0.0070)	0.0108** (0.0053)	0.0109** (0.0052)
$W\times$ *MD*	−0.0018 (0.0050)	−0.0030 (0.0047)	−0.0033 (0.0044)	−0.0032 (0.0044)
ρ	0.7657*** (0.0481)	0.7758*** (0.0456)	0.6367*** (0.0399)	0.6371*** (0.0394)
sigma_e	0.0007*** (0.0001)	0.0007*** (0.0001)	0.0007*** (0.0001)	0.0007*** (0.0001)
$log-likehood$	778.967	778.344	893.735	765.363
Hausman test p-value	0.0244	0.0139	0.0007	0.0002
R^2	0.2722	0.2373	0.1334	0.1313
Convergence rate	0.2691	0.2669	0.3552	0.3554
Observed number	360	360	360	360

Note: y means the level of regional green growth; IHCQ means the quality of innovative human capital; INDS means industrial structure; FDI means foreign direct investment; MD means marketization degree; "*", "**", and "***" indicate significance at the 10 %, 5 %, and 1 % levels, respectively. Standard errors are in parentheses.

instruments for IHCA and IHCQ. The fitness test of instrumental variables in this paper shows that the *P*-values of K–P rk LM are all 0.000, rejecting the unrecognizability of the instrumental variables; the values of K–P rk Wald F test are all greater than the critical value of 16.38, and the values of C-D Wald F test are all greater than the critical value of 10, indicating that there is no obvious problem of weak instrument variables, which means that the choice of instrumental variables is effective. The estimation results of the model using the above instrumental variables are shown in Table 11. The estimation results are still robust.

6. Discussion

The empirical results prove that IHC contributes significantly to regional green growth convergence in China. The results of this paper support Rocho'n's findings from a different perspective "China is in the same green growth convergence club with advanced and world growth frontiers economies such as India, Brazil and Malaysia" [13]. Rochon's findings only analyzed the performance of different countries in green growth convergence without delving into the main drivers of green growth convergence in these countries. The research findings of this paper, however, specifically reveal an important reason for China's green growth convergence - the driving force from IHC.

The results of this paper also strongly support the research findings of scholars from various countries on the impact of human capital on the ecological environment. Although the research approaches of these scholars are different, with some directly analyzing the impact of human capital on carbon emissions [30], and more analyzing the joint impact of human capital and one or more factors on the environment, most scholars have reached a common research conclusion that human capital can suppress carbon emissions and promote green growth and sustainable development [31–33,35,71]. The research findings of these scholars, in turn, corroborate the research results of this paper, although they have a common problem of homogenizing human capital and not considering its heterogeneity, thus ignoring the role of IHC. However, some scholars have considered this issue and studied the relationship between China's IHC and economic growth and carbon emissions, finding that IHC can suppress carbon emissions [40], which is consistent with the empirical results of this paper that IHC can promote China's regional convergence in green growth.

The research findings of this paper to some extent further broaden and deepen the study on the relationship between human capital and convergence of growth. Since the 1980s, the relationship between human capital and convergence of growth has been a focus of attention for scholars in various countries, but many scholars have studied the impact of human capital on traditional convergence of growth and ignored the impact of human capital on green growth convergence, as well as the impact of heterogeneous IHC on green growth convergence [45–47,50,72]. However, with the continuous deterioration of the earth's ecological environment, some scholars have studied the relationship between human capital and convergence of environmental efficiency [52]. Although the research perspectives of these scholars are different, their research findings have a high degree of consistency, namely, human capital has a positive impact on regional convergence of growth or environmental efficiency convergence in relevant countries, which is consistent

Table 11
The estimated results of the instrumental variable model.

Variables	IHCA		IHCQ	
	$W_{ij}{}^{d}$	$W_{ij}{}^{0-1}$	$W_{ij}{}^{d}$	$W_{ij}{}^{0-1}$
lny_{it-1}	−0.2317*** (0.0349)	−0.2852*** (0.0370)	−0.2335*** (0.0350)	−0.2872*** (0.0371)
IHCA	0.2512*** (0.0229)	−0.2423*** (0.0227)	/	/
IHCQ	/	/	1.6412 (1.3128)	1.5646 (1.3152)
$W\times$ lny_{it-1}	0.0937* (0.0583)	0.1581*** (0.0458)	0.0945* (0.0584)	0.1599*** (0.0458)
$W\times$ *IHCA*	−0.2106*** (0.0743)	−0.2902*** (0.0509)	/	/
$W\times$ *IHCQ*	/	/	3.1223*** (9.1276)	1.2378*** (2.9268)
ρ	0.7775*** (0.0410)	0.6354*** (0.0366)	0.7749*** (0.0418)	0.6352*** (0.0367)
Control variable	YES	YES	YES	YES
sigma_e	0.0007*** (0.0001)	0.0007*** (0.0001)	0.0007*** (0.0001)	0.0007*** (0.0001)
$log-likehood$	911.9287	894.116	912.0912	894.241
R^2	0.2442	0.2373	0.2501	0.1533
Observed number	420	420	420	420

Note: IHCA means the quantity of IHC; IHCQ means the quality of IHC; "*", "**", and "***" indicate significance at the 10 %, 5 %, and 1 % levels, respectively. Standard errors are in parentheses.

with the research findings of this paper.

7. Conclusion

Based on the data of green growth and IHC at the provincial level in China from 2004 to 2018, this paper constructs a dynamic panel model with spatial relevance. This paper empirically analyzes the effect of IHC on the convergence of green growth from the national level and regional level, and obtains the following main conclusions:

(1) There are obvious conditional β-space convergence characteristics of green growth among inter-provincial units in China. There are large differences in the conditional β spatial convergence characteristics of green growth under the spatial correlation expressed by distance weights and the spatial correlation expressed by neighborhood weights. Under distance weights, the models incorporating the quantity and quality of IHC had regional green growth convergence rates of 0.2946 and 0.2644, respectively; under neighborhood weights, the models incorporating the quantity and quality of IHC had regional green growth convergence rates of 0.3772 and 0.3426, respectively. The convergence speed of green growth under distance weight is significantly lower than that under adjacency weight, indicating that after considering complex spatial relationships, the convergence speed of green growth will decrease due to the existence of spatial spillover effects of green production activities.
(2) China's IHC has obvious convergence effect on green growth, and the space spillover or diffusion of innovative knowledge and technology is stronger under the distance weight, and the improvement of green growth rate is greater. At the national level, the inclusion of the quantity and quality of IHC under distance weighting increases the green growth convergence rate by 12.40 % and 0.88 %, respectively, and the inclusion of the quantity and quality of IHC under neighboring weighting increases the green growth convergence rate by 11.1 % and 0.91 %, respectively; this suggests that, although considering spatial correlation relationships that decay with distance decreases the green growth convergence speed, this complex spatial relationship increases the intensity of spatial spillover or diffusion of innovative knowledge and technology, which is conducive to the coordinated development of regional green growth.
(3) There is a club convergence phenomenon of green growth in the eastern and the Midwest parts of China, and the quantity and quality of IHC in the Midwest part of China play a stronger role in the convergence of green growth than that in the eastern part. The average effect of IHCA on the increase of green growth convergence rate in the eastern region is 18.68 %, and the average effect of IHCA on green growth convergence in the Midwest region is 48.75 %; the average effect of IHCQ on the increase of green growth convergence rate in the eastern region is 2.46 %, and the average effect of IHCQ on the increase of green growth convergence rate in the Midwest region is 5.04 %. The main reason for this phenomenon is that the eastern region has a higher level of green growth, and the space for green innovation of IHC is smaller and more difficult, while the Midwest region have a lower level of green growth and a scarcity of IHC, and the increase in IHC and the spatial spillover effect it generates have a significant effect on regional green growth.

The above conclusions reflect the significant effect of IHC on the convergence of regional green growth in China, further complement the research findings in the field of human capital and sustainable development, and reveal that the heterogeneity of human capital is an aspect that cannot be ignored. Further research on the combination of human capital heterogeneity and sustainable development will bring more theoretical and empirical discoveries. Based on the different convergence characteristics at the national and regional levels, this paper puts forward corresponding policy recommendations as follows:

(1) At the national level, there is an obvious conditional β spatial convergence of green growth among provincial units in China. This spatial convergence feature includes two kinds of spatial correlations: distance weights and neighbor weights. For different provinces, the convergence rate of green growth under the neighbor weight is significantly larger than that under the distance weight, which indicates that the convergence rate of green growth is faster among geographically neighboring provinces. Among the eight central provinces, except for Heilongjiang, the other seven provinces share borders with different eastern provinces. These seven central provinces should take advantage of this spatial correlation to give full play to the advantages of geographic proximity to the eastern provinces, increase learning from the bordering eastern provinces, and strengthen exchanges and cooperation between them, and accordingly, the corresponding eastern provinces should also increase their support for the green development of the central provinces bordering them. This will help the green growth level of these seven provinces to move closer to the green growth level of the eastern provinces bordering them, which can accelerate the convergence of green growth between the central and eastern provinces to a certain extent. Of the 12 western provinces, only Inner Mongolia and Guangxi border the eastern provinces of Liaoning, Hebei and Guangdong. With the advantage of geographic proximity, Inner Mongolia, Hebei and Shanxi established the "Golden Triangle Cooperation Area of the Great Wall of Mongolia, Jin and Hebei" in 2014. Led by the strategic goal of high-quality development, the three regions should strengthen cooperation in green development, strive for better and faster integration into the Beijing-Tianjin-Hebei integration and synergistic development, and accelerate the speed of interregional green growth convergence. Guangxi and Guangdong share a full border with each other and a common boundary line of about 931 km. The two regions began collaborative development in 1996, and over the past 27 years, Guangdong's help to Guangxi has produced obvious results. This kind of collaboration will continue, Guangxi should further improve the initiative of cooperation, make full use of its own advantages in resources, land and labor, learn from Guangdong's advances in green development, promote its own green growth faster, and deeply integrate into the Pan-Pearl River Delta Economic Circle, so as to effectively realize the green collaborative development between the two regions.

(2) At the regional level, the phenomenon of convergence of green growth clubs exists significantly in both the eastern and the Midwest regions of China. This shows that the eastern provinces and the Midwest provinces have similar internal conditions in economic and social aspects respectively, and their existing development basis is conducive to the convergence of green growth between them. Therefore, both the eastern provinces and the Midwest provinces should not only strengthen inter-provincial cooperation in green development, but also vigorously enhance intra-regional cooperation in green development. Specific measures include intra-regional talent exchange, technical cooperation and resource sharing, so as to promote coordinated development within the region. The previous empirical results show that the quantity and quality of IHC in the Midwest region have a stronger convergence effect on green growth than in the eastern region, indicating that the space and potential of the central and western regions in green development is larger than that of the eastern region, so the Midwest region should take full advantage of this advantage, on the one hand, to increase the cultivation of IHC in the region, and at the same time, to implement a strong human resources policy, improve the importation of innovative talents from the east and even abroad, so as to offset the negative effects of the siphon effect in the east, and effectively enhance the green growth speed and efficiency of the Midwest region, thus realizing the coordinated green development among the three regions more quickly, and ultimately achieving the grand strategic goal of high-quality development.

Just like the many other empirical researches, the study also contains some limitations. First, the study focuses on the regional level of China and may have aggregation problems. Further, because of the lack of data provided by statistical bureaus, the study conducted the empirical examinations for only 30 provinces of China, in the future, when more data can be collected, the study will include more provinces of China. In the future research, there are two main directions to be consider, one is more micro-level analyses of the impact of IHC, such as city-level even county-level, the other one is transnational research.

Data availability statement

The data that support the findings of this study are openly available in [CNKI] at https://kns.cnki.net/kns8s/?classid=HHCPM1F8.

CRediT authorship contribution statement

Xi Lin: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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