The effect of spatial structure of urban agglomerations on green development: Evidence from China

li Xuanting
Harbin Institute of Technology
Wang Xiaohong (hitwangxh@163.com)
Harbin Institute of Technology
Zhang Shaopeng (13251610878@163.com)
Harbin Institute of Technology

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Abstract

Spatial structure reflects physical urban agglomerations development and may have economic, societal, and environmental spillover effects. As China pays more attention to the construction of an ecological civilization and the green high-quality development of urban agglomerations, it is urgent to explore the impact of the spatial structure of urban agglomerations on green development. By using panel data of China's 16 urban agglomerations from 2004 to 2019, this study analyzes the dynamic impact, nonlinear relationship, mediating mechanism of spatial structure of urban agglomerations on green development. It is indicated that the spatial structure of urban agglomerations has a significant negative influence on green development, but there is a positive spatial spillover effect on green development in neighboring areas. And the results of the dynamic threshold model show that diverse environmental regulation intensities lead to different influences of spatial structure on green development. Moreover, technological innovation plays a partly mediating role in the relationship between the centrality of urban agglomerations and green development.

1 Introduction

Since its reform and opening up, China has experienced rapid urbanization, and the rate of urbanization has increased from 17.92% in 1978 to 64.72% in 2021. The massive concentration of population in cities and towns has absorbed the rural labor force and improved the efficiency of production factor allocation, which has played an important role in promoting high-quality economic development (Barca 2012). Urban agglomerations are an advanced form of spatial organization among cities, and such highly dense urbanized areas have gradually become the main form in China's new urbanization, as well as a vehicle or participating in global competition and taking over the world economy's shifting center of gravity. The development of urban agglomerations has, however, given rise to problems such as excessive internal traffic carrying pressure, serious environmental pollution, and ecosystem imbalances, as well as large disparities in economic development between cities of different scales. Solving the problem of coordinating the environmental and economic development of these urban agglomerations has become a key issue of common concern for both academics and policy makers.

As an indicator of regional development status, spatial structure is an important entry point for the exploration of regional law (Peris 2019). The spatial structure of urban agglomerations indicates the distribution and combination of different elements in space, and reflects of the degree of development of urban agglomerations. Whether or not the spatial structure is reasonable and orderly has an impact not only on ecological and environmental governance—because it affects the optimal allocation of urban cluster elements—but also on its centrality. The distribution characteristics of indicators reflect the spatial structure of the urban monocenter or polycenter, and the state of agglomeration and dispersion can have a spillover effect on green development (Meijers 2016). Building a reasonable and orderly spatial structure has been discussed in the literature from many different perspectives, but scholars have not yet reached a consensus on the relationship between the spatial structure of urban agglomerations and green development. There is thus a lack of judgment criteria for the optimization of the spatial structure of urban agglomerations, which also creates difficulties for planning preparation and policy formulation.

Based on the above considerations, this study poses the following research questions. Firstly, is the urban system structure of urban agglomerations reasonable? Secondly, how does the spatial structure of urban agglomerations affect green development? Thirdly, what are the main channels through which the spatial structure of urban agglomerations affects green development?

To answer these question, we took 16 urban agglomerations in China according to the national new urbanization plan (2014–2020) with 2004–2019 as the research period, and then used the centrality of the urban population scale to reflect the spatial structure of urban agglomerations. After constructing evaluation indexes, the entropy value method was used to reflect the level of green development. On this basis, the dynamic spatial Durbin models and dynamic panel threshold models were established to analyze the effects of the spatial structure of urban agglomerations on green development, as well as the associated mechanisms. This study expands the understanding of the spatial structure of urban agglomerations and its influence theoretically, which is conducive to coordinating the economic and environmental development of urban agglomerations, and it provides relevant references for decisions making to achieve sustainable urban development.

2 Literature Review

Urban agglomerations are multi-level complex network systems characterized by the dynamics of spatial extent and the development process. Existing studies are usually guided by the agglomeration theory of the new economic geography to characterize the spatial structure of urban agglomerations by choosing the centrality, which describes whether elements are distributed in one city or across multiple cities, as well as to what extent they are concentrated in cities or scattered elsewhere (Krehl 2019). Many scholars have measured centrality in terms of morphology and function. Morphological centrality is the most intuitive reflection of the spatial structure of urban agglomerations, and the degree of concentration of population and employment size is usually calculated using the fitness formula, the rank-order-size rule, the Mono index, or the Pareto index (Malý et al. 2015; Rauhut et al. 2017). Functional centrality emphasizes the intensity of different functional “flows” and the degree of connection each city in urban agglomerations. Wang (2019) used data on population, logistics, capital, and information flows to determine the spatial structure of urban agglomeration and found Guangzhou to be the core of the agglomeration. Liu (2016) posited that the spatial structure of urban agglomerations based on functional linkages is generally monocentric.

Over the past few years, the impact of changes in urban spatial structure on urban development had received extensive attention from scholars, and two main areas of research can be summarized based on existing studies. The first is economic growth effects, which include studies on how urban spatial structure affects economic efficiency and economic growth (Frick et al. 2016; Klimanov et al. 2017). The second is resource-environment effects, which include studies on how urban spatial structure affects resource use and pollution emissions. After a review of the existing literature, it appears most studies focus on a single perspective, such as how the evolution of urban spatial structure affects the economy or the environment specifically. Such fragmented research is not conducive to expanding our understanding of the relationship between changes in urban spatial structure and green development, and a more integrated research framework should be developed that would cover both the effects of economic growth and resource-environmental effects.

As urbanization progresses, the centrality of the spatial structure of urban agglomerations can reflect whether they are in a state of agglomeration economy or diseconomy and can further produce different effects. The scope of the agglomeration economic spillover effect promotes the concentration of factors to specific zones and achieves economic efficiency. When the cost of agglomeration exceeds the benefit, the regional spatial structure will shift toward polycentricity (Camagni 2017). Some scholars believe that the monocentric spatial structure is conducive to improving the economic efficiency of urban agglomerations (Bai et al. 2020; Wen et al. 2014). For example, Baileyn (2001) argue that monocentric urban areas show higher agglomeration effects than polycentric cities, while Parrjb (2002) argues that polycentric structures bring higher transportation costs and lower commuting efficiency, and the advantages of urban economies of scale are limited.

However, existing studies show that a polycentric spatial structure can lead to economic efficiency, because as the degree of monocentricity increases, it is often accompanied by diseconomies, and a shift from monocentric to polycentric can prevent the exacerbation of this phenomenon (Legallo et al. 2011; Meijers. 2018). Although they show different findings, the existing studies on the economic effects of the spatial structure of urban agglomerations all reflect that the spatial distribution of factors can affect the economy. It is indisputable that the urban agglomeration spatial structure can have an impact on the economy.

The relationship between economic growth and environmental pollution is a classic research topic in the field of environmental economics, and since the environmental Kuznets curve (EKC) was proposed, many scholars have conducted empirical studies on this relationship based on the EKC (Cortinovis et al. 2019; Meijers et al. 2010). The spatial structure of urban agglomerations affects the urban environment by influencing environmental processes, such as energy flow, material circulation, and biological processes. A reasonable spatial structure can improve the efficiency of transportation and reduce vehicle emissions, which is an effective way to promote green urban development (Bačić et al. 2014).

The above-mentioned studies have provided a rich research basis for further discussion, but there is still a need to further improve and fill the research gaps. Firstly, most of the articles focus on the perspective of urban agglomerations, but this paper deepens the research level and further raises the research perspective to the level of urban agglomerations; secondly, the current research is mainly focuses on the influence of economic growth and ecological environment, ignoring the influence path of the spatial structure of urban agglomerations on green development in the process of evolutionary formation; thirdly, most of the existing empirical studies on the spatial structure of urban agglomerations are based on the direct results of the spatial structure of urban agglomerations, and few empirical studies focus on the possible non-linear effects of the spatial structure of urban agglomerations. Based on this, this paper provides a theoretical basis and practical significance for further research on exploring the dynamics of promoting urban green development.

3 Theoretical Analysis And Hypotheses Development

3.1 Spatial structure of urban agglomerations and green development

The new economic geography, represented by Krugman (1991), argues that spatial agglomeration helps to achieve increasing returns to scale and provides a convincing theoretical explanation for factor accumulation in urban agglomerations at an early development stage. As the spatial structure is continuously optimized, urban agglomerations gradually shift from the early monocentric to a polycentric spatial structure, and the centrality gradually decreases (Hasegawa et al. 2019). However, the polycentric city structure is not simply a low-density dispersal; small cities around big cities can especially benefit from their proximity to larger cities (Krehl 2015; Yuan et al. 2014). For example, small cities can save transportation costs because they are within the service area for big city airports and other transit facilities, and the core cities in urban agglomerations can absorb the inflow of human resources and other factors from neighboring cities to further promote their own economic development. We can also call this kind of urban interaction a “mutual borrowing scale,” which can not only give full play to the advantages of core cities and their neighbors (Pereira et al. 2013), but also provide an agglomeration economy to the polycentric spatial structure of the sort enjoyed by a single megacity (Zambon 2017).

With the emergence of external diseconomies of scale in monocentric cities, the relevant economic agents in the central city will actively transfer intermediate products outward to save production costs (Rey et al. 2011). Given high inter-city communication costs, the rapid development of information technology and transportation facilities has brought cities closer to each other (Sohn 2005). City clusters can break the market segmentation between regions through the division of labor and collaboration between cities, thus forming development synergy (Taubenböck et al. 2017). This is primarily reflected in two aspects. On the one hand, the functions of the central city in the urban cluster are diffused in geographic space and regrouped at special nodes linked between cities, forming a spatial division in the labor layout of polycentric cities (Wang et al. 2019). The spillover effects of economic and ecological environmental protection are thus no longer limited by geographic space, enabling urban clusters to achieve green and sustainable development on a larger scale (Fabrizi et al. 2018; Noble et al. 2021). On the other hand, each enterprise production link is no longer limited to a certain city, but can reasonably be laid out with the comparative advantages of each city, effectively saving costs, reducing pollution, and continuously improving the green development level of urban clusters (Sarmiento 2018).

Based on the above analysis, we propose the first hypothesis.

H1: The centrality of the spatial structure of urban agglomerations has a negative influence on the green development.

3.2 Threshold effect of environmental regulation

The spatial structure of urban agglomerations involves the agglomeration and dispersion formed by the physical distribution of the interactions of development factors such as population and resources and the organization of activities inside and outside the city, as well as their combinations in the process of urbanization development (Glaeser 2016). During their evolution, cities are also prone to sloppy land use patterns, with sprawl leading to longer commuting distances, threatening the self-cleaning capacity of the urban ecosystems, and affecting the urban green development process (Veneri 2012). The different intensities of environmental regulations may have different effects on the green development process within urban agglomerations (Jebali 2017).

With the accelerated pace of ecological civilization construction, environmental protection and governance have gradually become the assessment index for local governments, which are paying more attention to solving environmental pollution problems than they did before (Han et al. 2020). When environmental regulation is limited, the population and resources are concentrated in the core city as the center of the core city grows, which leads to more sources of pollution as well as increased emissions. The government may focus on pursuing economic benefits and neglect environmental regulation, which results in the ineffective protection of the urban ecological environment and the inefficient use of resources and energy (Liu et al. 2018). This may be detrimental to the implementation of the national call for green development in urban clusters. As the intensity of environmental regulation increases, the effect of urban agglomeration centrality reaches a certain degree that may be conducive to cost savings, improving the efficiency of factor use, and promoting technological progress. If resources and the environment are taken as production input factors, agglomeration can help to improve the efficiency of factor use, which in turn will be conducive to the green and sustainable development of urban agglomerations.

Based on the above analysis, the second hypothesis is proposed.

H2: There is a significant threshold feature of environmental regulation influencing green development via the spatial structure of urban agglomerations.

3.3 Mediating effect of technological innovation

Through a review of the relevant literature, this study argues that the spatial structure of urban agglomerations can promote green development through technological innovation. In the evolution of urban agglomerations, there is a close correlation between the core cities and innovation upgrades to neighboring cities (Waiengnier et al. 2019). The quantity and quality of human capital in urban agglomerations constitute its talent stock, while technological accumulation is an important expression of the agglomeration’s core competitiveness. Both have a significant role in promoting the green development of urban agglomerations (Zhang et al. 2019). Technological innovation not only improves urban competitiveness but also enhances the green development of urban agglomerations through the knowledge spillover effect (Li et al. 2018). From a macroscopic point of view, the higher the centrality of the spatial structure, the more likely it is that the agglomeration has more than two economic development centers and possesses advanced technological advantages, which promotes the leap in the technological level from local to overall. Technological innovation thus becomes an important driving force to promote the economic growth, transformation, and upgrading of the urban agglomeration.

At the micro enterprise level, there is a certain gap in the development level between enterprises in core and non-core cities, resulting in the concentration of enterprises holding core technologies in core cities with abundant capital elements (Huang et al. 2019). With the increase of human capital and the accumulation of technology, the level of technological innovation in core cities is also increasing, because the human capital stock improves the industrialization level of technological innovation and increases the technological transformation capacity of urban clusters through spillover effect (Li et al. 2022). While technological diffusion is closely related to spatial proximity, and technological proximity can, to a certain extent, break the limiting effect of geographic space on technological spillover (Pumain 2019). Technological innovation to assist neighboring cities to cultivate innovation in science and technology-related platforms, which promotes the transformation of scientific and technological achievement and optimizes the industrial structure, thus significantly improving the green development level of urban agglomerations.

Based on the above analysis, the third hypothesis is as follows.

H3: Technological innovation has a mediating role on the relationship between urban agglomeration spatial structure and green development.

4 Model Construction And Variable Description

4.1 Models

4.1.1 Spatial weight matrix setting

To explore whether there is a spatial effect in the relationship between the spatial structure of urban agglomerations and green development, this study adopts Moran’s I index and constructs an economic-geographic weight matrix combining the economic and geographical characteristics of the urban development process in the form shown in Eq. (1).

$$W_{ij}^{e} = W_{ij}^{d} \times diag\left(\overline{X_1} / \overline{X}, \overline{X_2} / \overline{X}, \ldots\ldots \overline{X_n} / \overline{X}\right)$$

$$W_{ij}^{e} = \begin{cases} \dfrac{W_{ij}^{e}}{\sum_{j} W_{ij}^{e}}, i \neq j \\ 0, i = j \end{cases} \tag{1}$$

In Eq. (1), W_{ij} is the matrix element in the *i-th* row and *j-th* column, *d* reflects the geographic distance, which is the economic distance spatial weight matrix, and is the average value of GDP per capita of each province and city $_{j}$ in the observation period, which is the average value of GDP per capita of all provinces and cities in the observation period. In this paper, the standardized weights are noted as *W* after processing by row and standardization.

4.1.2 Spatial econometric model

To mitigate the effects of heteroskedasticity, extreme values, and units of measure, and considering the time dependence of green development, this study constructs a dynamic spatial Durbin model in logarithmic form with a one period lag of the explanatory variables on the basis of the static spatial Durbin model. The specific model is constructed as follows.

$$Ingd = \rho \sum_{j=1}^{n} W_{ij} \ln gd_{it-1} + \delta_1 \sum_{j=1}^{n} W_{ij} \ln apoly_{it} + \delta_n \sum_{j=1}^{n} W_{ij} \ln X_{it} + \beta_0 + \beta_1 \ln apoly_{it} + \beta_n \ln X_{it} + u_i + v_t + e_{it} \tag{2}$$

In Eq. (2), *gd* denotes green development; *apoly* denotes spatial structure centrality of urban agglomerations; β_0 is a constant term; β_1,β_n represent coefficients of influencing factors, respectively; W_{ij} reflects a spatial weight matrix, *X* denotes a control variable, ρ reflects a spatial regression coefficient, δ denotes a spatial effect coefficient, υ_i means a city fixed effect, v_i is a time fixed effect, and e_{it} presents a random error term.

4.1.3 Dynamic panel threshold model

The traditional linear regression method cannot solve the problem of structural mutation (Yao et al. 2020). In this study, the impact of urban agglomeration spatial structure on green development may vary with the intensity of environmental regulation and present different characteristics. In other words, different intervals of environmental regulation intensities may create different impacts, and there is likely a nonlinear relationship between spatial structure and green development. The panel threshold model originally proposed by Hansen (1999) can be used to further examine the changes in spatial structure on the level of green development at different intervals of environmental regulation intensity. The model expression is as follows.

$$\ln gd_{it} = \sigma_i + \lambda_0 \ln gd_{it-1} + \lambda_1 \ln apoly_{it} I(\ln eri_{it} \leq \gamma) + \lambda_2 \ln apoly_{it} I(\ln eri_{it} \succ \gamma) + \lambda_n \ln X_{it} + \theta_i + \tau_t + o_{it} \tag{3}$$

$$\ln gd_{it} = \mu_1 \sum_{j=1}^{n} W_{ij} \ln tech_{it} + \mu_2 \sum_{j=1}^{n} W_{ij} \ln X_{it} + \alpha_0 + \alpha_1 \ln tech_{it} + \alpha_2 \ln X_{it} + \sigma_i + \kappa_t + \varepsilon_{it} \tag{4}$$

$$\ln gd_{it} = \tau \sum_{j=1}^{n} W_{ij} \ln gd_{it} + \pi_1 \sum_{j=1}^{n} W_{ij} \ln apoly_{it} + \pi_2 \sum_{j=1}^{n} W_{ij} \ln tech_{it} + \pi_3 \sum_{j=1}^{n} W_{ij} \ln X_{it} + \lambda_0 + \lambda_1 \ln apoly_{it} + \lambda_2 \ln tech_{it} + \lambda_3 \ln X_{it} + \omega_i + \varphi_t + \gamma_{it} \tag{5}$$

In these equations, ln*gd* denotes green development; ln*apoly* is the spatial structure of urban clusters; ln*eri* means the intensity of environmental regulation; *I()* reflects the indicative function; σ_i ,$a_{0,}$ λ_0 stands for the constant term; λ_1, λ_2, λ_n, a_1,, a_2 present the coefficients of the influencing factors; *X* represents the control variable; μ_1, μ_2,π_1, π_2,, π_3 denotes a spatial effect coefficient, θ_i, σ_i, ω_i denotes the urban fixed effect, τ_t, κ_t, φ_t means the time fixed effect, and o_{it}, ε_{it}, γ_{it} represents the random error term.

4.2 Variables

(1) Green development (*gd*). This study's primary dependent variable was green development. The Green Development Index System formulated by the National Development and Reform Commission and other departments in 2016, it is the first comprehensive index system for green development officially released in China, and it reflects the key areas of green development specified in the 13th Five-Year Plan (Mao et al. 2017; Huang et al. 2017). In the subsequent 14th Five-Year Plan, the importance of green development and the promotion of high-quality urban development were once again proposed. This study refers to relevant studies and selects 14 evaluation indicators from the three dimensions of growth quality, green ecology, and social livelihood, as shown in Table 1, to construct a system to evaluate green development (Graham 2010; Li et al. 2020). The entropy value method was used to standardize the 14 indicators to determine indicator weights.

Table 1
The evaluation index system of green development

Primary Indicators	Secondary Indicators	ertiary Indicators	Indicator Description	Attributes
Green development	Quality of growth	GDP per capita gross domestic product	GDP / Total population	□
		Urbanization rate	Resident population/total population by province	□
		Foreign Trade Dependence	Total imports and exports/GDP	□
		The proportion of secondary industry	Secondary industryValue added/GDP	-
		The proportion of tertiary industry	Tertiary sector value added/GDP	□
		Science and technology investment intensity	Science and technology budget expenditure / total fiscal budget expenditure	□
	Green Ecology	Industrial wastewater discharge intensity	Industrial wastewater discharge/industrial value added	-
		Industrial waste gas emission intensity	Industrial CO_2 emissions/industrial value added	-
		Industrial smoke (dust) emission intensity	Industrial smoke (dust) emissions / industrial value added	-
		Greening coverage of built-up areas	Greening coverage of built-up areas	□
	Society and People	Income gap between urban and rural residents	Ratio of urban to rural residents' income	-
		Number of libraries	Number of libraries per 10,000 people	□

(2) Spatial structure of urban agglomerations (*apoly*). The Spatial structure of urban agglomerations is used as independent variable in this paper. Referring to the research results of some scholars, the spatial structure of urban agglomerations is measured using the place-order-scale rule (Cao et al. 2019; Gabaix et al. 2011), and the specific formula is as follows.

$$\ln P_i = \ln P_i - q \ln R_i \quad (6)$$

In Eq. (6), P_i *means* the population size of city i, N_i is the city with the largest population size in the city cluster, R_i represents the ranking position of city i's population size in the city cluster, and q indicates the spatial centrality of the city cluster. When $q = 1$, the city population scale conforms to Chipov's law, when $q > 1$, it means the city cluster has monocentric structure, when $q < 1$, it means the city cluster has polycentric spatial structure.

(3) Environmental regulation intensity (*eri*). This paper adopts environmental regulation intensity as threshold variable. According to previous studies (Rastvortseva et al. 2020; Vasanen et al. 2012), indicators such as industrial wastewater, industrial fume and dust emissions and industrial CO_2 emissions were selected and the entropy method was used to calculate the environmental regulation intensity (*eri*).

(4) Technological innovation (*tech*). The mediating variable of this study is technological innovation. According to the relevant studies, the technology market turnover is selected to measure technological innovation (Hua et al. 2017).

(5) In order to avoid errors in the empirical results due to incorrect omission of variables, this paper selects several control variables based on the existing research (Timiryanova et al. 2020). Specifically, human capital (*hu*) is expressed by the number of college students in each city; wage level (*wage*) is measured by the average wage of working employees; medical infrastructure (*hos*) is expressed the number of medical beds; financial development (*fan*) is measured by the year-end deposit and loan balance of financial institutions as a proportion of GDP; industrial structure (*it*) is expressed by the proportion of tertiary industry in GDP.

Combined with the availability of data, the time span selected for this study is 2004–2019, and all original data were obtained from the China Statistical Yearbook, China Urban Statistical Yearbook and China Urban Construction Statistical Yearbook for the previous years. To eliminate the effect of price increases, 2004 was selected as the base year, and the GDP of all cities in the 16 major urban agglomerations for the remaining years was deflated. For a few missing items, data based on the linear interpolation method were provided.

5 Empirical Analysis

5.1 Spatial autocorrelation test

Moran's I index was used to test the spatial correlation, and due to the limitation of space, the results of typical years are reported in Table 2. The test results show that the original hypothesis of no spatial autocorrelation is rejected for both the spatial structure of urban agglomerations and green development at the 1% significant level. This indicates that green development has spatial autocorrelation and will be influenced by the spatial structure of urban agglomerations in neighboring areas, and the empirical model needs to include the spatial interaction effect of the spatial structure of urban agglomerations and green development.

Table 2
The results of Spatial autocorrelation test

	Spatial structure of urban agglomerations		Green Development	
Year	Moran's I	Z-score	Moran's I	Z-score
2004	0.301***	3.154	0.265***	2.915
2005	0.284**	2.004	0.275***	3.024
2006	0.275***	2.895	0.283***	3.934
2007	0.356***	3.246	0.279***	2.706
2008	0.315*	1.302	0.242*	1.064
2009	0.304***	3.195	0.258***	2.576
2010	0.256**	2.302	0.231***	2.938
2011	0.257***	3.246	0.245***	2.731
2012	0.323**	2.126	0.278***	2.315
2013	0.327***	3.231	0.254***	2.691
2014	0.335***	3.241	0.237**	1.546
2015	0.326***	3.205	0.244***	2.683
2016	0.319***	2.895	0.236*	1.064
2017	0.308***	2.315	0.279***	2.667
2018	0.341***	2.759	0.285***	2.548
2019	0.343***	3.015	0.279***	2.691

5.2 Results of spatial econometric model identification and estimation

This study first analyzes the impact of the spatial structure of urban agglomerations on green development using full-sample data. Based on the results of the Hausman test, the fixed-effects model was selected and individual and time double fixed were set. In addition to the dynamic spatial Durbin model, the dynamic panel system GMM analysis was conducted during this part of the full-sample analysis process to gain a more comprehensive understanding of the impact of spatial structure on green development and to increase the robustness of the analysis results. According to the regression results in Table 3, the regression coefficient of the spatial structure reflected by centrality is negative and passes the significance test, indicating that the higher the centrality of the urban agglomeration spatial structure, the less favorable the effect on green sustainable development.

Observe the empirical results of the dynamic spatial Durbin model, from Table 3, we can see that the regression coefficient of green development with a one-period lag is negative, this also proves that green development has a time lag and the scientificity of using the dynamic spatial econometric model. The influence of centrality on green development is negative, it means that high spatial structural centrality has a negative influence on green sustainable development, so hypothesis H1 holds. The higher the centrality of urban agglomerations, leading to the concentration of population and enterprises in the same city. In turn, this results in environmental pollution and imbalanced economic development.

The regression results for the control variables led to the following conclusions. Specifically, the impact of human capital, the number of medical beds and financial development on green development is significantly positive, while the influence of wage level and industry structure on green development is significantly negative.

Table 3
The results of full sample estimation

	Dynamic Panel GMM Model	Dynamic Spatial Durbin Model
Variables	ln*gd*	
lngd_{t-1}	-0.604***	-0.342***
	(-3.985)	(-4.013)
ln*apoly*	-0.021***	-0.032***
	(-2.641)	(-3.236)
ln*hu*	0.018*	0.024**
	(1.957)	(2.102)
ln*wage*	-0.029***	-0.031***
	(-3.265)	(-4.213)
ln*hos*	0.024**	0.021*
	(2.053)	(1.836)
ln*fan*	0.002***	0.003*
	(3.967)	(1.879)
ln*it*	0.033***	-0.039***
	(4.998)	(-5.074)
W*ln*apoly*		0.003*
		(1.931)
Time fixed effects	YES	
Urban fixed effects	YES	
ρ		0.631***
		(4.215)
R^2	0.296	0.447

Note: *, **, *** represent 1%, 5%, and 10% significance levels, respectively. The t-statistic values are indicated in parentheses and the same as in the following table. ln*gd* denotes green development, ln*apoly* represents the spatial structure of urban agglomerations, ln*hu* is human capital, ln*wage* stands for the wage of working employees, ln*hos* presents the number of medical beds, ln*fan* denotes financial development, ln*it* represents industry structure.

	Dynamic Panel GMM Model	Dynamic Spatial Durbin Model
sargan	0.821	
LogL		703.25
N	2224	2224

Note: *, **, *** represent 1%, 5%, and 10% significance levels, respectively. The t-statistic values are indicated in parentheses and the same as in the following table. ln*gd* denotes green development, ln*apoly* represents the spatial structure of urban agglomerations, ln*hu* is human capital, ln*wage* stands for the wage of working employees, ln*hos* presents the number of medical beds, ln*fan* denotes financial development, ln*it* represents industry structure.

5.3 Results of spatial effect decomposition

Based on the Lesage et al. (1998) studies to arrive at an accurate estimate of the impact of the spatial structure of urban agglomerations on green development, effect decomposition based on the dynamic spatial Durbin model is required. The results are shown in Table 4.

In the short term, the coefficients of both direct and indirect effects are positive and pass the level of significance. It means that the influence of an urban agglomeration spatial structure on green development as reflected by centrality has a positive influence on both local and neighboring areas. This may be because, as centrality increases, factors tend to cluster in the core large cities, and agglomeration, as a compact form of economic spatial movement, can generate economic benefits and play a positive role in the green development of local and neighboring areas.

In the long term, the indirect effect and the total effect both pass the level of significance and have positive coefficients, while the direct utility coefficient is negative. This result means that, with the increase of centrality, the core cities can hardly sustain the load of the larger population and living pressure in the long-term, which is not conducive to high-quality development. However, owing to the excessive pressure of the local urban agglomerations, it is difficult for the economy and the environment to attract more factors to pour in, resulting in factors flowing into the surrounding areas and promoting economic growth in the surrounding areas. With the influx of high-quality talent, the level of technological innovation effectively improves the quality of the original ecological environment and promotes its green development.

Table 4
The effect decomposition results of dynamic spatial Durbin model

	Decomposition of short-term effects			**Decomposition of long-term effects**		
	Direct	Indirect	Total	Direct	Indirect	Total
ln*apoly*	0.013**	0.026*	0.039**	-0.011**	0.027*	0.016**
	(2.378)	(1.907)	(2.154)	(2.324)	(1.857)	(2.309)
Note: ln*apoly* represents the spatial structure of urban agglomerations.						

5.4 Robustness tests

The robustness of the present results was ensured by replacing the spatial weight matrix and the independent variables with a robustness test. The spatial geographical distance matrix was selected for regression analysis again, and the empirical results are shown in Table 5. The coefficient of the effect of spatial structure on green development reflected by centrality passes the significance test, and its influence coefficient is negative and spatial effect coefficient is positive. The direction and strength of the control variables are generally consistent with the previous study, indicating the robustness of the empirical results. The results of the regression analysis of the explanatory variables using the super-efficiency SBM model measuring total green factor productivity with undesired output yields are shown in Table 5, the robustness of the empirical results is verified.

Table 5
The results of robustness test

	ln*gd*	
Independent variables	Replacement space weight matrix	Substitution variables
ln*apoly*	−0.021**	−0.326**
	(-2.364)	(-2.315)
W*ln*apoly*	0.132**	0.124*
	(2.054)	(1.973)
Control variables	YES	
Time fixed effects	YES	
Urban fixed effects	YES	
ρ	0.185***	0.156
	(3.258)	(0.312)
R^2	0.316	0.198
LogL	753.89	84.56
N	2224	2224

Note: ln*gd* denotes green development, ln*apoly* represents the spatial structure of urban agglomerations,

6 Further Analysis

6.1 Threshold regression results

Before conducting the threshold regression, it is necessary to test the significance of the threshold effect of the model. Based on the self-sampling method, F-statistic and its p-value are calculated in this paper, and the results of the self-sampling test with environmental regulation as the threshold variable are presented in Table 6. The results prove that the three-threshold model passes the significance test. After obtaining the threshold values, we constructed a dynamic panel threshold model with environmental regulation as the threshold variable. The estimation results of this model are listed in Table 7. The empirical results show that the spatial structure centrality of urban agglomerations affects green development to different degrees under different levels of environmental regulation, which implies that there is a nonlinear association .

Table 6
Threshold effect test

Model	F-value	Estimated value	P-value	BS times	Threshold			95% confidence interval
					10%	5%	1%	
Single Threshold	13.401	3.246	0.034	500	4.979	8.965	16.926	[3.238,3.254]
Double threshold	9.213	4.867	0.003	500	5.795	8.631	16.598	[4.861,4.873]
Triple Threshold	3.246	5.769	0.042	500	6.574	8.431	15.646	[5.762,5.778]

Table 7
Regression results of dynamic panel threshold model

	Minimal environmental regulation intensity	Less intense environmental regulation	Higher intensity of environmental regulation	Extremely strong environmental regulation
	$\ln eri \leq 3.246$	$3.246 < \ln eri \leq 4.867$	$4.867 < \ln eri \leq 5.769$	$\ln eri > 5.769$
ln*apoly*	-0.921**	0.104**	0.186**	-0.881
	(-3.261)	(2.412)	(-2.439)	(-1.237)
Constant term	0.219***	0.763***	0.645**	0.548*
	(3.214)	(3.012)	(2.126)	(1.926)
Control variables	YES			
Time fixed effects	YES			
Urban fixed effects	YES			
R^2	0.341	0.401	0.337	0.219
N	2224	2224	2224	2224

Note: ln*gd* denotes green development, ln*apoly* represents the spatial structure of urban agglomerations, ln*eri* means environment regulation intensity.

As shown in Table 7, the influence of centrality on green development is reflected in the spatial structure, and there is a significant nonlinear relationship under the heterogeneity of environmental regulation intensity—a three-threshold effect. When the intensity of environmental regulation is lower than the threshold value and the coefficient (− 0.921), showing that when the intensity of environmental regulation is very small, change of centrality has a significant inhibitory effect on green development. This may be due to the fact that as the centrality of core cities increases, the government focuses on pursuing economic benefits and neglects environmental regulation, resulting in ineffective protections of the urban ecological environment and inefficient resource and energy use.

When the intensity of environmental regulation is between the threshold values of 3.246 and 4.867, the coefficient of the influence of the centrality on green development is 0.375. Perhaps because of the fact that, with the rapid economic development, the population and resources are gradually concentrated in the core cities, leading to an increase in pollution sources as well as an increase in emissions. Although it is difficult for the government to coordinate balanced economic development and environmental protection in a short period of time, measures are necessary to rectify the environmental pollution problem and gradually explore a suitable environmental regulation model to cope with sustainable urban development.

When the intensity of environmental regulation is between the threshold values of 4.867 and 5.769, the coefficient of centrality on green development is 0.186, which passes the 5% significance level test. This is primarily due to the fact that when centrality reaches a certain level, the effect of agglomeration will be conducive to cost savings, improved efficiency of factor use, and promotion of technological progress.

When the intensity of environmental regulation is greater than the threshold value of 5.769, the coefficient of the effect of centrality on green development is negative. This may be because multi-city agglomeration causes serious pollution while forming a shared economy, so local governments may adopt strong environmental regulations that force enterprises to innovate green. Thus, economic growth and environmental protection have not been effectively balanced, which hinders green development of the urban agglomeration.

Based on the above analysis, the centrality of the spatial structure of urban agglomerations appears to have a non-linear relationship with their green development, and there is a three-threshold effect. With the strengthening of environmental regulations, the spatial structure of polycentric urban agglomerations weakens the negative impact on urban green development, but maintains the appropriate level of regulation—that is, hypothesis 2 holds. This also reflects that most of China’s urban agglomerations are adjusting their contained urban planning, rationalizing their spatial layout, and promoting sustainable and healthy urban development.

6.2 Mechanism Analysis

6.2.1 Mediation model construction

In order to explore the mechanism of spatial structure of urban agglomerations on green development in more details, the mediating effect model is verified by using stepwise regression method, and the specific model settings are as follows: model 6 tests the influence of urban spatial structure on green development; model 7 tests the influence of spatial structure of urban agglomerations on technological innovation; model 8 tests the intermediary effect of technological innovation. The conditions for the mediating effect model to hold are as follows.

$$\ln gtfp_{it} = \partial_0 + \beta_1 \ln poly_{it} + \beta_2 \ln X_{it} + \mu_i + \nu_t + \varepsilon_{it} \tag{7}$$

$$\ln tech_{it} = \chi_0 + \delta_1 \ln poly_{it} + \delta_2 \ln X_{it} + \phi_i + \varphi_t + \iota_{it} \tag{8}$$

$$\ln gtfp_{it} = \kappa_0 + o_1 \ln poly_{it} + o_2 \ln tech_{it} + o_3 \ln X_{it} + \upsilon_i + \rho_t + \kappa_{it} \tag{9}$$

In these equations, ln*gtfp* denotes green development; lna*poly* is urban spatial structure; ln*tech* is technological innovation; χ_0 is a constant term; δ_1, δ_2, o_1, o_2, o_3 denote the coefficients of influencing factors; X is a control variable; Φ_i, v_i are urban fixed effects, φ_t, ρ_t are time fixed effects, τ_{it}, κ_{it} are random error terms.

6.2.2 Analysis of empirical results

From the results in Table 8, it can be seen that the coefficient of the total effect of the spatial structure of urban agglomerations on green development in column (1) passes the significance test and is negative, which can be verified in the next step; the regression coefficient of the spatial structure of urban agglomerations on technological innovation in column (2) is negative, while the estimated coefficient of the spatial structure of urban agglomerations on green development in column (3) is negative and significant at the 5% level, showing that there is an indirect effect, which can be continued. Finally, the regression results in column (3) show that the coefficient of the direct effect of spatial structure of urban agglomerations on green development is also significantly negative.

The above results represent that technological innovation plays a partially mediating role in the relationship between the spatial structure of urban agglomerations and green development, hypothesis 3 is valid. Possible because with the evolution of urban agglomerations, the core cities in urban agglomerations are closely related to the innovation and upgrading of neighboring cities, and technology accumulation is an important manifestation of the core competitiveness of urban agglomerations, which as a key factor to promote the green development of urban agglomerations. Not only improves the competitiveness of cities but also enhances the green development of urban agglomerations through the knowledge spillover effect.

Table 8
Regression results of mediating effects

	Model(1)	Model(2)	Model(3)
Independent variables	ln*gd*	ln*tech*	ln*gd*
ln*apoly*	-0.002***	-0.105*	−0.003**
	(-3.236)	(-1.878)	(-2.054)
ln*tech*			-0.011**
			(-2.353)
Control variables	YES		
Time fixed effects	YES		
Urban fixed effects	YES		
ρ	0.631***	0.257*	0.264*
	(4.215)	(1.984)	(1.821)
R^2	0.447	0.519	0.465
LogL	703.25	407.89	721.83
N	2224	2224	2224
Note: ln*gd* denotes green development, ln*apoly* represents the spatial structure of urban agglomerations, ln*tech* means technological innovation.			

7 Conclusions And Implications

7.1 Conclusion

Using data from China's 16 urban agglomerations from 2004 to 2019, this paper constructs green development indicators from the three dimensions of quality of growth, society and people and green ecology. In the process of empirical analysis, we first used used the double fixed-effect dynamic spatial Durbin model and the system GMM to analyze the impact of spatial on green development. With the purpose of exploring whether there is a non-liner relation between the spatial structure of urban agglomerations and green development. This paper also conducted the dynamic panel threshold regression using environmental regulation intensity as a threshold variable.Finally, this paper used a mediating effect model to study the mediating transmission of technological innovation.

The results show that, firstly, the centrality of urban agglomerations plays a negative role in affecting green development, but there is a positive spatial spillover effect on the level of green development in neighboring areas. Secondly, there is a nonlinear relationship between the centrality of urban agglomerations and green development; that is, under different environmental regulatory intensities, the centrality of urban agglomerations impacts green development to varying degrees, the negative influence of the centrality of urban agglomerations diminishes as the strength of environmental regulation increases. Thirdly, the impact of the centrality of urban agglomerations on green development is moderated by technological innovation.

7.2 Policy implications

In accordance with the findings that emerge from this study, the following policy implications are recommended:

First, although the polycentric spatial structure of urban agglomerations can bring economic benefits, attention should also be paid to environmental pollution. It is first necessary for urban agglomerations to take the path of intensive, compact, and connotative green development; make efficient use of spatial resources; and improve the actual construction and efficient utilization of urban space. Because problems such as excessive differences in economic development in different cities may occur within urban agglomerations, building a city network with a clear division of labor and synergistic development is an important step in the pursuit of green development.

Second, it is necessary to strengthen the economic cooperation and construction of transportation infrastructure between different cities, and to guide different cities in a policy of joint prevention and treatment of environmental pollution. The over-concentration of elements can easily lead to inefficient resource allocation and ecological pollution, so city clusters can minimize environmental pollution and realize scale borrowing through the overall planning of industrial structure and economic development.

Finally, green technology innovation can be improved, the government guides enterprises to actively engage in green technology activities, urges them to invest part of their capital in green innovation or use less polluting energy, optimizes industrial and energy structures, responds to the inherent demands of high-quality economic development and global climate governance, and makes full use of the positive external effects of a green economy.

7.3 Research limitations

This study also has some limitations. Firstly, although we measured the independent variable as comprehensively as possible by constructing an indicator system, it has not been able to reasonably solve the problem of incomplete construction of the indicator system. Therefore, under the condition of considering the comprehensive construction of the indicator system, how to make a more accurate measurement of green development is yet to be further expanded by subsequent studies. Secondly, our study is based on the Chinese context to explore the effect of spatial structure of urban agglomerations on green development, which is something that needs to be continued to be explored for other countries and economies in the future.

Declarations

Acknowlegements

Ethics declarations

Ethics approval and consent to participate.

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Consent for publication

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Competing interests

The authors declare no competing interests.

Author Contributions

All authors contributed to the study conception and design. Data analysis and the improvement of the article were by Shaopeng Zhang. The proposal of research ideas, the construction of the main framework were by Xiaohong wang. The first draft of the manuscript was written by Xuanting Li and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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