Spatiotemporal Evolution and Driving Factors of Green Development Efficiency in Gansu Province: Postprint

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Date: 2023-03-15T00:00:00+00:00

Abstract

Improving green development efficiency is crucial for the ecological civilization construction and high-quality development of Gansu Province. This study employs the Super-SBM model, hotspot analysis, and geographical detector to analyze the spatiotemporal evolution characteristics and driving factors of green development efficiency in 14 cities and prefectures of Gansu Province from 2005 to 2019. The results show that: (1) Temporally, green development efficiency exhibits an overall "M-shaped" fluctuation trend, with regional relative differences also showing corresponding fluctuation patterns. (2) Spatially, green development efficiency demonstrates significant spatial differentiation, with the north-south gradient difference substantially larger than the east-west direction. The degree of spatial agglomeration is weak, dominated by low-hotspot, medium-hotspot, and low-coldspot areas, exhibiting club convergence characteristics. (3) Marketization level, innovation capability, government regulation, and urbanization level are the dominant factors of spatial differentiation in green development efficiency. The green development efficiency of Gansu Province is the result of multi-factor interaction. The research findings not only enrich the urban green development indicator system and research cases, but also provide references for the green transformation and development of Gansu Province and other underdeveloped regions.

Full Text

Spatiotemporal Evolution and Driving Factors of Green Development Efficiency in Gansu Province

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Abstract: Improving green development efficiency (GDE) is crucial for ecological civilization construction and high-quality development in Gansu Province. Using the Super-SBM model, hotspot analysis, and geographic detector model, this study analyzes the spatiotemporal evolution characteristics and driving factors of GDE in 14 cities and prefectures of Gansu Province from 2005 to 2019. The results show that: (1) Temporally, GDE exhibits an "M-shaped" fluctuating trend, with regional relative differences showing a corresponding fluctuation pattern. (2) Spatially, GDE demonstrates significant spatial heterogeneity, with the north-south gradient difference substantially greater than the east-west difference. The degree of spatial agglomeration is weak, dominated by low hot-spot areas, medium hot-spot areas, and low cold-spot areas, exhibiting characteristics of club convergence. (3) Marketization level, innovation capacity, government regulation, and urbanization level are the dominant factors driving the spatial differentiation of GDE. The GDE of Gansu Province results from the interaction of multiple factors. These findings not only enrich the index system and case studies of urban GDE but also provide references for green transformation development in Gansu Province and other less-developed regions.

Keywords: green development efficiency; Super-SBM model; geographic detector model; Gansu Province

1 Introduction

In the 21st century, human society has entered the green industrial revolution, and the development model is shifting from the "black development model" to a comprehensive "green development model"[?]. Since China's reform and opening-up, remarkable achievements have been made in economic construction, with significant improvements in industrialization and urbanization levels. However, high-quality socio-economic development is also constrained by resource and environmental issues [?]. In 2005, Comrade Xi Jinping proposed the concept that "lucid waters and lush mountains are invaluable assets," leading to the rapid rise of the green development model [?]. On April 25, 2015, the "Opinions on Accelerating the Construction of Ecological Civilization" issued by the Central Committee of the Communist Party of China and the State Council proposed adhering to "green development, circular development, and low-carbon development" as the basic approach [?]. The 19th National Congress report pointed out the need to accelerate the reform of the ecological civilization system and promote green development. The "14th Five-Year Plan" and the long-range objectives for 2035 further emphasize building an ecological civilization system and promoting a comprehensive green transformation of economic and social development. Therefore, promoting regional green development is not only essential for solving regional development problems but also an inevitable requirement for implementing national strategies.

The core concept of green development is circular, low-carbon, and sustainable development, with the key lying in improving green development efficiency. Research on green development efficiency has attracted widespread attention from scholars both domestically and internationally, focusing on three main aspects: (1) **Regional selection**: Current studies mainly concentrate on global [?], national [?], urban [?], and watershed [?] scales. (2) **Evaluation system construction and research methods**: The green development efficiency measurement index system is primarily built based on theories of green development and sustainable development [?], inclusive development theory [?], etc. Specific research methods include the projection pursuit model [?], the "three-circle system" theory [?], and input-output analysis [?]. In recent years, green development efficiency evaluation based on input-output analysis methods, which constructs inputs of human resources, capital, technology, and resource elements, as well as desired outputs of economic, social, and ecological benefits and undesired outputs considering environmental costs, has shown significant advantages, with scholars conducting extensive work in this area [?]. (3) **Mechanism analysis**: Exploring the influencing mechanisms of regional green development efficiency helps grasp the root of green development issues. According to the "First Law of Geography," many studies have employed spatial Durbin models [?], geographically weighted regression [?], system GMM estimation [?], etc., to analyze the impacts of environmental regulation [?], industrial structure adjustment [?], market allocation [?], and other driving factors on green development.

In summary, existing literature has become more diversified in research scales and methods. However, studies on green development efficiency in less-developed areas with significant potential demand for green development and late-mover advantages remain limited. Although Gansu Province serves as a golden node in the "Belt and Road" initiative, a key province for high-quality development in the Yellow River Basin, and an important ecological security barrier in western China, its endogenous comparative advantages are insufficient, urgently requiring green development to force a transformation of the regional development model. The 4th "Gansu Qilian Mountain Summit Forum" proposed focusing on "Integrating Intelligence into Longyuan, Green Transformation," seeking new paths for green development in Gansu under new circumstances. How to achieve "doing something while refraining from doing others" and strive to create a "Gansu model" for Beautiful China? To this end, this paper constructs a GDE index system with Gansu characteristics and regional universality based on Gansu' s regional features, employs the Super-SBM model to measure the GDE of 14 cities and prefectures in Gansu Province, characterizes their spatiotemporal evolution features, and uses the geographic detector model to construct a driving factor model for GDE. This study aims to enrich the index system and case studies of urban GDE while providing references for green transformation development in Gansu and other less-developed areas.

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2 Data and Methods

2.1 Data Sources and Processing

Based on the "three-circle system" theory of green development and referencing the "Green Development Index System" issued by the National Development and Reform Commission, this study follows the principles of data availability, scientificity, objectivity, and systematic consistency to establish the GDE input-output index system for Gansu Province (Table 1). Regarding input indicators, capital input varies due to different depreciation rates and base-period capital stocks. Drawing on Shi et al. [?], this study selects total fixed asset investment of the whole society as the representation. Labor input, technology input, and resource input are represented by the number of employed persons at year-end [?], full-time equivalent of R&D personnel [?], and comprehensive resource input index [?], respectively. For desired outputs, economic output is represented by GDP at constant 2005 prices [?]. Social output is comprehensively reflected by the social benefit index. Environmental benefit, representing "good" environmental output, is represented by the environmental benefit index [?]. For undesired outputs, the environmental pollution index is used. Considering that Gansu is a major agricultural province where chemical fertilizers have significant environmental impacts, this study follows Lin et al. [?] by including the amount of chemical fertilizer converted to pure quantity. The resource input comprehensive index, social benefit index, environmental benefit index, and environmental pollution index are all calculated through the entropy method. Data are primarily sourced from the *China City Statistical Yearbook*, *Gansu Development Statistical Yearbook*, and statistical yearbooks and bulletins of various cities and prefectures. Missing data are filled through interpolation.

Table 1 Evaluation index system of green development efficiency in Gansu Province

Category	Indicator	Unit
Input indicators	Labor element	Number of employed persons
	Resource element	Total water, land, and energy consumption

Category	Indicator	Unit
	Capital element	Total fixed asset investment of the whole society
	Labor input	Number of employed persons at year-end
	Technology input	Full-time equivalent of R&D personnel
	Resource input	Built-up area
		Total electricity consumption of the whole society
		Artificial and natural gas supply
		Liquefied petroleum gas supply
Desired outputs	Economic benefit	Per capita disposable income of urban residents (constant 2005 price)
		Total retail sales of consumer goods
	Social benefit	Green coverage rate
		Harmless treatment rate of domestic waste
	Environmental benefit	Industrial waste gas emissions
Undesired outputs	Environmental pollution	Industrial wastewater emissions

Category	Indicator	Unit
		Chemical fertilizer converted to pure quantity

2.2 Methodology

2.2.1 Super-SBM Model The Super slacks-based measure (Super-SBM) model considers the "slack" effect of factors, effectively solving the problem of evaluation result bias caused by ignoring undesired outputs in GDE assessment. It also overcomes the defect that effective decision-making units cannot be effectively sorted and distinguished in traditional DEA models. Since inputs of traditional resources, labor, capital, and science and technology can produce not only desired outputs but also undesired outputs such as environmental pollution, the Super-SBM model can truly reflect the essence of GDE in Gansu Province. The specific formula is:

$$\min \frac{1 + \frac{1}{m}\sum_{i=1}^{m} \frac{s_i^-}{x_{io}}}{1 - \frac{1}{r_1+r_2}\left(\sum_{q=1}^{r_1} \frac{s_q^g}{y_{qo}^g} + \sum_{u=1}^{r_2} \frac{s_u^b}{y_{uo}^b}\right)}$$

Subject to:

$$\begin{cases} x_o = X\lambda + s^- \\ y_o^g = Y^g\lambda - s^g \\ y_o^b = Y^b\lambda + s^b \\ s^- \geq 0, s^g \geq 0, s^b \geq 0, \lambda \geq 0 \end{cases}$$

where ω is the GDE value; x, y_q, and z_u represent input, desired output, and undesired output elements, respectively; m, r_1, and r_2 are the numbers of input, desired output, and undesired output indicators; s_i^-, s_q^g, and s_u^b are the slack variables of input, desired output, and undesired output, respectively; k is the production period; n is the number of decision-making units; θ_j is the weight vector.

2.2.2 Hotspot Analysis (Getis-Ord Gi*) The Getis-Ord Gi* statistic is used for local spatial correlation analysis, which can identify spatial clustering of different cities in Gansu and reflect the spatial dependence and heterogeneity of GDE. The specific calculation formula is as follows [?]:

$$G_i^*(d) = \frac{\sum_{j=1}^{n} \lambda_{ij}(d) X_j}{\sum_{j=1}^{n} X_j}$$

where X_j is the GDE value of spatial unit j; d is the critical distance; λ_{ij} is the spatial weight. For $G_i^*(d)$, a Z-test is required. A significantly positive Z-value indicates that the spatial unit is a high-value cluster area, belonging to a GDE hotspot, and vice versa for a cold spot.

2.2.3 Geographic Detector Model The geographic detector [?] uses a set of statistical methods to explain the driving forces behind spatial differentiation of factors and detect the interaction effects of two factors on the explanatory power of an element. It is more reliable than classical regression when the sample size is less than 30. It can analyze both quantitative and qualitative data and has been widely applied in ecological environment changes and socio-economic development. The formula is as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2}$$

where q is the explanatory power; N and σ^2 are the sample size and variance, respectively; L is the number of strata of the detection factor; N_h and σ_h^2 are the sample size and variance of stratum h ($h = 1, 2, \ldots, L$), respectively. The q value ranges between [0,1], with larger values indicating stronger explanatory power.

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3 Results

3.1 Spatiotemporal Differentiation Characteristics of GDE in Gansu Province

Using SOLVERPRO 5.0 software, the Super-SBM model was applied under input-oriented and constant returns-to-scale assumptions to calculate the GDE of Gansu Province (Green Development Efficiency, GDE) from 2005 to 2019.

3.1.1 Temporal Evolution Characteristics of GDE in Gansu Province By analyzing the mean value and coefficient of variation of GDE in Gansu Province (Figure 2), the overall trend shows an "M-shaped" fluctuation pattern, which is opposite to the urban development trend found by Zhou et al. [?]. The coefficient of variation exhibits a corresponding fluctuation trend with four distinct stages:

Stage 1 (2005-2007): GDE fluctuated upward, and the coefficient of variation fluctuated upward. During this period, China's accession to the WTO gradually deepened international trade cooperation, and Gansu Province was influenced by this radiation effect, with improved technical production conditions and enhanced resource allocation efficiency, leading to continuous GDE improvement. Additionally, during China' s "11th Five-Year Plan" period, Gansu, located in western China with a weak foundation, focused on economic development and undertook a large number of industrial transfers from eastern regions, resulting in a small GDE increase. However, varying economic development levels and capital inputs across regions, along with different emphases on ecological civilization construction, led to a substantial increase in regional relative differences.

Stage 2 (2008-2011): GDE fluctuated downward, while the coefficient of variation fluctuated upward. During this stage, the financial crisis eliminated backward production capacities and invested in emerging technology industries. Environmental regulation was strengthened, but regional relative differences continued to fluctuate upward due to varying implementation effects.

Stage 3 (2012-2015): GDE fluctuated upward, and the coefficient of variation fluctuated upward. With the implementation of the "Five-in-One" development strategy, GDE improved, but Gansu Province' s foundation was weak, leading to continued fluctuations in regional disparities.

Stage 4 (2016-2019): GDE fluctuated downward, and the coefficient of variation fluctuated downward. With the advancement of energy conservation and emission reduction during the "13th Five-Year Plan" period, Gansu Province built a national ecological security barrier, adhering to ecological priority and green development. However, due to policy lag effects, efficiency improvements were not immediately reflected. Low-efficiency cities showed a clear catch-up effect on high-efficiency cities, and regional relative differences fluctuated downward.

Figure 2 [Figure 2: see original paper] Temporal evolution of GDE in Gansu Province from 2005 to 2019

3.1.2 Spatial Differentiation Characteristics of GDE in Gansu Province

Using ArcGIS software, global trend maps were drawn with fitted values (Figure 3), and spatial pattern maps were created using the natural breaks method (Figure 4) to explore the distribution characteristics of GDE in Gansu Province.

Significant spatial heterogeneity. Both east-west and north-south directions show inverted "U-shaped" trends. In 2005, the north-south direction showed a pattern of high in the west and low in the east, and high in both north and south with low in the middle. In 2010, the differences between east-west and north-south directions narrowed significantly, showing overall relative equilibrium. In 2015, the east-west gap expanded rapidly again, forming a gradient pattern of high in the west and low in the east, with slightly higher efficiency in central regions. In 2019, the north-south gap further expanded, forming a pattern of high in both north and south with low in the middle. Comparatively, the north-south gradient difference is significantly greater than the east-west difference, indicating that narrowing the north-south gap remains a key focus for future policy regulation.

Figure 3 [Figure 3: see original paper] Trends of spatial patterns of GDE in Gansu Province

Figure 4 [Figure 4: see original paper] Spatial differentiation of GDE in Gansu Province

Weak spatial agglomeration. The Getis-Ord Gi* index was used to visualize GDE values (Figure 5). Overall, the spatial clustering characteristics of GDE in Gansu Province are weak, with significant areas dominated by low hot-spot areas, medium hot-spot areas, and low cold-spot areas. Most regions maintain their original patterns over time. In terms of spatial distribution of cold and hot spots: due to favorable location conditions and agricultural and livestock-based industrial structures with low environmental costs, a low hot-spot area centered on Gannan Tibetan Autonomous Prefecture formed in 2005. A low cold-spot area centered on Lanzhou and Baiyin cities formed in 2010, reflecting high economic development inputs and large environmental costs. A medium hot-spot area centered on Jinchang and Wuwei cities formed in 2015, where heavy industry-based industrial structure adjustment promoted GDE improvement. From the perspective of different efficiency regions, medium-efficiency areas have the highest proportion; the number and proportion of high-efficiency areas increased; and the proportion of low-efficiency areas decreased, indicating that GDE in Gansu Province has improved but has not fundamentally changed. At the city level, Lanzhou, with the best economic conditions, has the lowest GDE, which is consistent with Li et al. [**?**], suggesting that economic development and ecological construction have not formed a coordinated and symbiotic virtuous cycle, and the economic development mode remains relatively extensive with prominent environmental issues. Jinchang, Zhangye, and Jiayuguan cities show an upward trend in GDE, with certain achievements in developing ten major green ecological industries. Gannan Tibetan Autonomous Prefecture, Linxia Hui Autonomous Prefecture, and Longnan City have relatively high GDE, mainly due to their development of agriculture, animal husbandry, and tourism with smaller environmental costs. The GDE shows characteristics of spatial club convergence.

Figure 5 [Figure 5: see original paper] Spatial agglomeration characteristics of GDE in Gansu Province

3.2 Analysis of Driving Factors

To further reveal the spatial clustering characteristics and evolution patterns of GDE, this study constructs a driving factor model for GDE in Gansu Province and uses the geographic detector to analyze the dominant factors of spatial differentiation and their interactions.

3.2.1 Selection of Driving Factors Drawing on relevant research findings [**?**, **?**, **?**, **?**, **?**, **?**] and considering the "pattern" characteristics of GDE in Gansu Province, this study selects urbanization level, industrial structure, government regulation, trade level, marketization level, innovation capacity, and population density to verify influencing factors of GDE, constrained by data availability. Specifically, urbanization level is represented by the proportion of urban population to total regional population; industrial structure by the ratio of secondary industry output value to tertiary industry output value; government regulation by the proportion of fiscal expenditure to GDP; trade level by the total value of import and export commodities of each city; marketization level by the proportion of non-state-owned and non-collective employed personnel; innovation capacity by the sum of science, technology, and education expenditures as a proportion of GDP; and population density by the population number per unit land area.

3.2.2 Analysis of Detection Results Identification of dominant factors in GDE spatial differentiation. Factor detection (Table 2) shows that except for government regulation and innovation capacity in 2005, all other factors passed significance tests at the 0.01 level. Overall, marketization level, innovation capacity, government regulation, and urbanization level are the dominant factors, with mean q-values greater than 0.1. Trade level, population density, and industrial structure are relatively weaker. Among them, urbanization level, government regulation, and innovation capacity have great potential influence on future GDE spatial differentiation, with q-values reaching 0.234, 0.231, and 0.207 in 2019, respectively. Over time, the q-values of government regulation and innovation capacity show an upward trend, while those of trade level, marketization level, and population density show a downward trend.

The q-value of marketization level is the strongest. Marketization level achieves efficient allocation of resource elements through market competition mechanisms, price feedback mechanisms, supply-demand balance mechanisms, and risk warning mechanisms. Although Gansu Province has improved its marketization level, it remains relatively low, limiting its enhancement capacity.

Regarding innovation capacity, clean production technology, resource efficiency improvement technology, and pollution control technology can promote efficient resource utilization and environmental pollution control, improving input-output efficiency and enhancing environmental governance effectiveness. As a northwest inland region, Gansu faces significant brain drain and weak scientific and technological innovation capacity. This also verifies that the "forced mechanism" of technological innovation proposed by Zhou et al. [**?**] has not yet been formed.

In terms of government regulation, local finance has a top-down "directive" development characteristic, playing a policy preference dividend role that facilitates ecological compensation and ecological construction, building Gansu's western ecological security barrier.

Regarding urbanization level, Gansu's urbanization level continues to rise, improving socio-economic development welfare and strengthening ecological civilization concepts and green development demand. This can promote the government to strengthen and improve the environmental governance system and enhance environmental governance capacity. On the other hand, the factor agglomeration effect and spatial spillover effect of urbanization development can synergistically integrate industries and enterprises, reduce production process costs, improve input-output efficiency, and promote industrial chain reshaping, optimization, and industrial transformation and upgrading.

The q-value of industrial structure is the weakest. The rationalization and advancement of industrial structure are significant for economic benefits, resource utilization efficiency, and reducing the stress effect on resources and environment. For Gansu, industry is dominated by heavy industries such as petrochemical and non-ferrous metal smelting, attracting many factors to flow into resource-based industries. There is a need to promote the development of the tertiary industry and optimize the industrial structure.

Regarding trade level, Gansu is located in northwest inland China with a weak foundation. Import and export trade produces environmental spillover effects, gradually diffusing concepts of sustainable development, green technology, and ecological culture. Sustainable development mechanisms and advanced environmental governance systems have promoted the rapid improvement of GDE in Gansu to a certain extent. However, vigilance is needed against lowering environmental access thresholds for foreign enterprises under competitive pressure for investment attraction, as the resulting resource and environmental problems will constrain GDE improvement.

The q-value of population density is weak and shows a downward trend. Population density exerts pressure on regional ecological protection, resource utilization, and environmental quality, reducing per capita resource availability, causing continuous expansion of production and living spaces and continuous shrinkage of ecological spaces. The severe resource and environmental situation caused by rising population density in Gansu promotes GDE improvement, which is similar to the research conclusions of Cheng et al. [**?**].

Interaction effects of driving factors on GDE spatial differentiation. To further explore the interaction effects of different driving factors on GDE, this study uses ArcGIS software to first discretize numerical variables into categorical variables and then uses the geographic detection model for calculation. The interaction detection results of driving factors from 2005 to 2019 (Table 3) show that the interaction types are mainly double-factor enhancement and nonlinear enhancement. Among them, the interaction effect of marketization level and innovation capacity (X_5 X_6) reached 0.9 in both 2005 and 2019, indicating that the combination of driving factors has strong explanatory power consistent with the spatial differentiation of GDE in Gansu, strongly explaining the degree of GDE spatial differentiation. The GDE of Gansu Province is the result of interactions among multiple factors.

Table 2 Factor detection results of spatial differentiation of GDE in Gansu

Province

Factor	2005	2010	2015	2019	Mean
Urbanization level (X_1)	0.156**	0.178**	0.201**	0.234**	0.192
Industrial structure (X_2)	0.034**	0.041**	0.038**	0.045**	0.040
Government regulation (X_3)	0.087	0.143**	0.189**	0.231**	0.163
Trade level (X_4)	0.112**	0.098**	0.087**	0.076**	0.093
Marketization level (X_5)	0.267**	0.245**	0.223**	0.201**	0.234
Innovation capacity (X_6)	0.069	0.123**	0.165**	0.207**	0.141
Population density (X_7)	0.098**	0.087**	0.076**	0.065**	0.082

Note: q is the explanatory power. ** indicates significance at the 0.01 level.

Table 3 Interactive detection results of spatial differentiation of GDE in Gansu Province

Interaction	2005	2010	2015	2019	Interaction Type
X_1 X_2	0.287	0.312	0.341	0.378	Double-factor enhancement
X_1 X_3	0.356	0.421	0.489	0.567	Nonlinear enhancement
X_1 X_4	0.298	0.301	0.324	0.356	Double-factor enhancement
X_1 X_5	0.456	0.489	0.523	0.567	Nonlinear enhancement
X_1 X_6	0.334	0.398	0.467	0.534	Nonlinear enhancement
X_1 X_7	0.287	0.298	0.312	0.334	Double-factor enhancement
X_5 X_6	0.901	0.887	0.876	0.912	Nonlinear enhancement

Note: represents double-factor enhancement; represents nonlinear enhancement.

4 Discussion

This study constructs a GDE index system for Gansu Province. Compared with previous studies [?, ?], this research includes the amount of chemical fertilizer converted to pure quantity in the undesired output index system, better reflecting Gansu' s characteristics and regional universality. The spatiotemporal analysis of GDE in Gansu shows that due to differences in input factors and policies, each city and prefecture focuses on different elements in the green development transformation, leading to regional heterogeneity characteristics. Moreover, existing studies mostly explore the impact of single or few factors on GDE, while this paper uses the geographic detector to explore the dominant control factors of GDE spatial differentiation and the superimposed contribution rates of different factors, which is more conducive to studying the heterogeneous characteristics of each factor' s impact on GDE.

The driving factor detection results for GDE in Gansu indicate that improvements can be made by: enhancing the ecological economy level, promoting high-quality economic development, improving resource and environmental carrying capacity, implementing ecological protection and restoration projects for mountains, rivers, forests, farmlands, lakes, and grasslands; establishing urban and regional circular development systems, strengthening research and development of green development common technologies, resource-efficient utilization, and environmental pollution control; strengthening government regulation, focusing on the driving effect of multi-factor synergy on green development transformation; scientifically and precisely controlling territorial space, optimizing the proportion of "production-living-ecological" space, and improving the sustainable development benefits of territorial space structure optimization. Due to different resource endowments, allocation efficiency, and development priorities across cities and prefectures, Gansu should implement different development strategies.

Regarding spatial evolution, the spatial differentiation of GDE is significant, with the north-south gradient difference greater than the east-west difference. GDE has improved but has not fundamentally changed. Lanzhou shows the lowest GDE, while Gannan Tibetan Autonomous Prefecture, Linxia Hui Autonomous Prefecture, and Longnan City show relatively high GDE. Jinchang, Zhangye, and Jiayuguan cities show an upward trend in GDE. The degree of spatial agglomeration is weak, mainly consisting of low hot-spot areas, medium hot-spot areas, and low cold-spot areas, with most regions maintaining their original patterns. Gannan Tibetan Autonomous Prefecture is a low hot-spot area, Lanzhou and Baiyin cities formed a low cold-spot area in 2010, and Jinchang city formed a medium hot-spot area in 2015. The GDE shows characteristics of spatial club convergence, and there remains a long way to go to improve GDE.

Furthermore, this study uses the prefecture-level city as the research unit. Future research should further use remote sensing technology to quickly obtain data at a batch level and refine the scale, attempting to explore GDE measurement and spatiotemporal evolution processes based on grid scales, and study the driving mechanisms of GDE in Gansu from a multi-dimensional composite perspective combined with the human-environment relationship perspective.

5 Conclusions

This study analyzes the spatiotemporal evolution characteristics and driving factors of GDE in Gansu Province from 2005 to 2019 using the Super-SBM model, Getis-Ord Gi* analysis, and geographic detector model. The main conclusions are:

1) **Temporal evolution**: During the study period, GDE in Gansu Province showed an "M-shaped" four-stage fluctuation trend. Both GDE and regional relative differences exhibited an "M-shaped" fluctuation pattern, with 2007, 2011, and 2015 being the three major turning points. Under various regional policy backgrounds, different cities showed different development trends.
2) **Spatial evolution**: The spatial differentiation of GDE is significant, with the north-south gradient difference substantially greater than the east-west difference. The degree of spatial agglomeration is weak, dominated by low hot-spot areas, medium hot-spot areas, and low cold-spot areas, with most regions maintaining their original patterns. Gannan Tibetan Autonomous Prefecture is a low hot-spot area. In 2010, a low cold-spot area centered on Lanzhou and Baiyin cities formed. In 2015, a medium hot-spot area centered on Jinchang city formed. The GDE shows characteristics of spatial club convergence.
3) **Driving factors**: The driving factors exhibit regionalization, dynamism, and complexity. Marketization level, innovation capacity, government regulation, and urbanization level are the dominant factors driving the spatial differentiation of GDE in Gansu Province. Urbanization level, government regulation, and innovation capacity have great potential influence, with their q-values reaching 0.234, 0.231, and 0.207 in 2019, respectively. The q-values of government regulation and innovation capacity show an upward trend, while those of trade level, marketization level, and population density show a downward trend. The GDE of Gansu Province is the result of multifactor interaction.

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Note: Figure translations are in progress. See original paper for figures.