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Evaluation of Green Development Efficiency of the Major Cities in Gansu Province, China

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Abstract: Green development (GD) has become a new model of sustainable development across the world. However, our knowledge of green development efficiency (GDE) in Gansu province is poor. In remedy, this study, based on the panel data of 12 major cities in Gansu from 2010 to 2017, employed the super-efficient Slack-based measure (SBM) to analyze and evaluate GDE from the input–output perspective. Furthermore, we analyzed the input redundancy and output deficiency of identified inefficient cities in 2017 and conducted spatial autocorrelation analysis of GDE of the cities under study. Results show differences in the GDE of the major cities in Gansu, with an average value of 0.985. Green development efficiency in Lanzhou, Qingyang, Jinchang, Jiuquan, and Tianshui was relatively higher than in other cities. Green development efficiency in Zhangye, Wuwei, Jiayuguan, Baiyin, Dingxi, Longnan, and Longnan was less than one due to their redundant labor and capital input and excessive pollutant emission output. The overall GDE in Gansu depicts "high east and low west" zones. Each city in Gansu needs to formulate targeted policies and regulations to improve resource utilization, innovation capacity, reduce pollutant emission, optimize the industrial structure, and promote inter-city cooperation to construct a sustainable green economy.

Keywords: green development efficiency; sustainable development; super-efficient SBM; GIS; Gansu province

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1. Introduction

Green development (GD) is a new model of sustainable development that centers on social, economic, and environmental stewardship to promote human wellbeing through efficient natural resource utilization that fosters the provision of ecosystem services [1,2]. These ecosystem services include improved air and water quality for human survival [3,4], enhanced biodiversity in towns and cities [5], and resource-use efficiency [6,7]. Since the outbreak of the international financial crisis in 2008, the United Nations have been advocating for a "Green New Deal". In this regard, the forces of GD in global cities and towns are gaining unprecedented recognition [8], with the hope of protecting the environment and sustainably promoting economic recovery. These have led to reduced pollution emission [9] and increased efficiency of natural resource-use for social [10], environmental [11], and economic wellbeing of humans [4]. However, there is variation in the GD status of countries at the national [9], regional [12,13], and global levels [8].

Green development is crucial to overcoming societal, economic, and environmental challenges in the coming decades. The link between GD and human wellbeing denotes equal distribution and access to a quality environment [2]. The United States is one of the foremost countries to stimulate GD through its investment in clean energy [14]. Similarly, the EU has built "green industry" while Japan's strategy towards realizing the green economy includes a low-carbon society, sound material-cycle society, and living in harmony with nature [15]. Developing countries such as Cambodia and South Africa have also developed strategic plans to attain green economy status [16,17]. Furthermore, recent evidence has shown that less utilization of water and the production of less waste from water is an essential indicator of GD [3]. Other studies show that GD is positively related to GDP [18], the efficiency of energy utilization [4], and negatively correlated to the emission of Sulphur dioxide, which depends on compliance with government regulation [1].

China has a large population with limited per capita resources [19]. Since the reform and opening up, China has experienced unprecedented development in just over 30 years compared to developed countries in the West. China's extensive production methods and a waste of resources concerning its rapid economic development has increased environmental pollution [20]. In this context, China's GD is imperative. Presently, China is one of the largest economies, the highest energy consumer [14], and the strongest advocate of GD in the world [11,21], leveraging on socioeconomic development, ecological construction, and investment in renewable energy sources [4,22]. According to [11], GD in China increased steadily from 2003 to 2016 in the eastern, northeastern, central, and western regions. Reference [23] reported that GD indicators (e.g., forest cover, social development) increased by 14.7% after returning farmlands to forests. Thus, China's GD experience is worthy of sharing with other developing countries worldwide [10]. For example, China has incorporated GD into the Belt and Road Initiative (BRI) to narrow the gap between advanced and developing countries in this regard [24].

Different indicators of sustainable development have been developed in previous studies. Reference [25] used a "socio-economic indicator for the bio-economy" (SEIB) to examine member states' socio-economic performance. The study grouped member states into virtuous (e.g., Denmark, Portugal, and Austria), in-between (e.g., France, Germany, Belgium), and laggard (e.g., United Kingdom, Czech Republic, and Malta) states based on the European average SEIB. In another study, [26] assessed the status of sustainable development in 35 Organisation for Economic Co-operation and Development OECD countries concerning the UN 2030 Agenda using economic, social, and environmental indicators to represent Sustainable Development Goals (SDGs). Both the ranks and sustainable development indicator scores of the OECD countries differ, with the top-performing countries identified as Denmark, Finland, Iceland, Sweden, and Norway. The worst countries in rank and performance are Chile, Italy, Mexico, Turkey, and Greece. Green development can be viewed as a practical way of achieving sustainable development [27]. Based on panel data from 28 provinces in China and using research and development expenditure input as a key indicator, [28] found differences in green development efficiency (GDE) of the provinces with Beijing (1.273) and Shanxi (0.219) ranking the highest and lowest, respectively. Similarly, [29] reported that in spatial terms, China's green innovation efficiency is unbalanced across the 30 provinces considered in their study from 2009–2017. Green innovation efficiency is higher in the eastern region than the national level, while the other regions are central > western > northeastern. However, it is worth mentioning that China views GD as a prerequisite for sustainable development [27].

The existing literature on urban GD in China mostly focuses on GDE at the national [11,27] or regional scale [4,30], with little attention given to the quantitative evaluation of GD at the city and municipal level. Understanding the current status of development at these levels can promote GD practices in localities through concrete feasibility planning [31,32]. More importantly, studies on GD in China (e.g., [10]) and other regions of the world (e.g., [8]) lack in-depth analysis of spatial dependence. Moreover, the research evaluation scale mostly reflects the temporal characteristics of regional GD only, neglecting the structural issues of spatial dependence. GD's status in China is currently tending to be more effective with energy utilization and economic output [4]. However, there is room for improvement in Chinese GD due to unbalanced development among its regions and cities [21,33]. Earlier studies (e.g., [28]) show that GDE in Gansu is low and ranks 25th among the 30 Chinese provinces used in the study [30]. To this end, our knowledge of GD in the cities in Gansu province is still limited.

2. Theoretical Background

In recent times, "green development" has been an opportunity [34] and fundamental to the attainment of sustainable development [27]. It is increasingly gaining acceptance across the globe. Green development's essential feature is considering natural resources [6] and the environment [10] as driving factors of social and economic development. For example, green innovation technology can improve the performance of firms [4]. Green building potentially reduces energy consumption [35], and improved environmental indicators could promote GD, as the Yangtze River Delta of China's experience has demonstrated [10]. Furthermore, researchers have reported positive outcomes of GD practices on energy consumption [36], pollutant treatment and utilization [23], CO_2 emission [21], and SO_2 emission [1], but not natural resource use [37]. Consequently, environmental managers and policymakers shift their attention towards green product development through GD practices [38]. Therefore, it is important to understand the spatio–temporal association of GD at the micro-level through empirical quantification.

This section summarizes GD based on theory and the context of this study. After that, we review some important aspects of green development, drawing on the existing literature.

2.1. Green Development

The theoretical definition of GD relates to the integration of economic, ecological, social, and environmental stewardship as defined by many scholars. The study in [5] defined GD as a panacea to simultaneously achieve development and economic growth while preventing biodiversity loss, environmental degradation, and indiscriminate natural resource use. The work in [10] considers GD as a model of advancement established within the constraint of environmental, ecological, and resource carrying capacities towards the realization of sustainable development. From the perspective of eco-industry, the authors of [39] explain GD as fostering a low-carbon economy through green economic policies that seek to adjust factor prices and taxation, rather than high energy consumption that leads to high pollution, to attain a modern economic growth intertwined with circular and sustainable development. Green development promotes a harmonious relationship between humans and nature [40]. Notably, GD is innovative [1] and proactive, having potential benefits for future generations [27].

According to [1], GD has three main features. First, the goal of GD should center on sustainable economic and environmental development. Second, ecological and environmental resources are fundamental elements of social and economic development. Third, the GD approach should focus on greening tendency within the context of the process and consequences of economic activities. Therefore, GD's purpose is to advance the status quo of economic growth [41], and its ultimate goal is to protect the ecological environment and existing or ongoing developments [4]. Whereas some scholars argue that GD is a distinct pathway of achieving sustainable development [42], others contend that the GD concept far outweighs sustainable development [27]. It suffices to say that GD's theoretical premise is the symbiotic relationship between natural, economic, and social systems and the complex positive and negative interactions between them [43]. Thus, in the context of this study, GD encompasses the constraints of pollutant treatment and utilization, ecological efficiency, social and economic development [27], energy consumption [27], and the efficient allocation of labor and capital input [28].

2.1.1. The Chinese Context of Green Development

In Chinese parlance, GD is a pre-requisite for sustainable development [27]. Across the 40 years of reform and China's opening up [44], the country has passed through different stages of developmental evolution such as "disordered development", "black development", "circular development", and the present transition to GD [45]. The Chinese central government proposed green development in its 12th Five Year Plan in 2011 [27]. Similarly, at the Fifth Plenary, in the 18th the communist party of china CPC Central Committee session, the Chinese government pointed out the need to adhere to GD practices through compliance with state environmental policies (e.g., energy conservation, emission reduction). Over time, research on GD has attracted the interest of researchers and policy-makers [27]. Therefore, GD potentially promotes the construction of a beautiful China [45] alongside its contribution to global resource-use efficiency and ecological security.

Moreover, the Chinese government views GD as an essential tool for human, ecological, and social development in the present and future. More importantly, the connotation of Chinese GD encompasses the living environment [23], rational energy consumption [28], pollutant emission reduction [10], natural resource conservation [46], and other issues related to sustainable development. As one of the top world economies, China's GD has far-reaching implications on global sustainable development and economic prosperity. This justifies the extent of GD research in China, which majorly focuses on national, regional, and industrial levels, suggesting the need for more in-depth GD studies at the city and municipal level.

2.1.2. Green Development Efficiency (GDE)

To intuitively understand GD dynamics, researchers introduced the concept of "efficiency" to quantify it [27,28]. From the theoretical analysis, green development efficiency is important because it provides a basis for comparing GD at the global, national, regional, and city levels. The study in [28] examined the provincial GDE in the Chinese iron and steel industry. The authors found that GDE decreased from 0.628 in 2006 to 0.571 in 2015, representing an annual decrease of 1.1%. Furthermore, capital investment positively influenced GDE in the eastern and western regions, while the latter (i.e., GDE) was negatively affected by industry scale and energy structure in the central region. Using a framework of human–environment interaction at the regional level, the study in [45] found that GDE increased by 10% from 2005–2015, and that high-efficiency cities had positive spillover effects on the low efficient cities. In northeast China, the authors of [44] reported that foreign direct investment and economic development are positively correlated to GDE, while environmental regulation and energy consumption negatively correlates with GDE. The study in [47] classified China's provincial GDE into rising, U-shaped, and falling. The result from their study shows that urbanization, environmental protection, energy conservation, and policies targeted at emission reduction enhance GDE, while human capital was negatively related to it.

2.2. Stakeholders in Green Development

The stakeholders involved in GD are the government, enterprises, Non Governmental Organization (NGOs), and the public [1]. Specifically, GD policy regulations are issued by the government and guided by the NGOs; enterprises play the role of implementing the regulations while the public oversees the implementation process [1,48]. Whereas public participation is positively related to GD [1], potential economic and environmental benefits are important drivers of stakeholders' decision in this regard [2]. This suggests that government regulations should be imposed with caution because an enterprise can settle for a strategy that considers huge profit at the expense of promoting GD [46]. For example, the government of Canada restricted producing and importing incandescent light bulbs into the country but promoted the use of other alternative energy-efficient light sources (e.g., compact fluorescent light bulbs, CFLs) [49]. Similarly, plastic foam containers were banned in Zimbabwe due to the emission of toxic chemicals when heated. In remedy, the Environment Management Agency of Zimbabwe ordered the use of biodegradable packages in restaurants [50]. These approaches show how the government as a stakeholder could influence GD by considering the trade-off between the enterprises' sustainability and the environment.

2.3. Incentives for Green Development

The adoption of GD practices is affected by different means of public participation [1]. The incentive to participate in GD can be internal (i.e., government policies and regulations) or external (i.e., economic efficiency) [38,51]. Whereas external incentives force beneficiaries to fulfill specified conditions to benefit from GD, those leveraging on internal incentives are motivated by the potential benefit of promoting GD [38]. For example, the Chinese government incentivized green building by granting 45 RMB per sqm and 80 RMB per sqm subsidies to two-star and three-star buildings, respectively [52]. Analyzing data from 49 countries along the Belt and Road Initiative (BRI), reference [24] found spatial differences in GD levels varying from high to low along the east–west direction. The authors reported that economic development cooperation, sustainable cooperation and environmental governance cooperation promotes GD in developing countries.

In China, the positive drivers of GD include corporate regulatory compliance, environmental administrative decentralization [1], land-related policies [53], socioeconomic elements [11], urbanization and technological innovation [30], trading of carbon emission [9], invention patents and green technology patents [54], and development of improved water resource management techniques [3]. On the other hand, the factors that hinder GD include corporate ownership structure, dependence on foreign investment, fiscal policy [30], and the discharge of wastewater into lakes and rivers leading to severe water pollution across the majority of provinces in China [3]. Nevertheless, the government of China remains a strong advocate of GD.

2.4. Green Development Evaluation System

The basis of conducting GD evaluation is a systematic and complete index system [23]. Reference [10] used the population–resources–environment–development–satisfaction model to study the regional GD of Yangtze River Delta (YRD) and found improved environmental indicators (e.g., pollution control, emission intensity) are the most important avenue to promote GD in the YRD region. Reference [55] evaluated the GDE of the Central Plains Urban Agglomeration from 2007 to 2016 using the super-efficient Slack-based measure (SBM) and Malmquist index from static and dynamic perspectives. The temporal and spatial differentiation characteristics of GD among sub-cities of the Central Plains Urban Agglomeration were examined. Their result indicates that the overall GD level of the Central Plains urban agglomeration is low, and the impact of technological progress on GDE is high during the study period. In addition, the study reported regional differences in GDE and weak interactions among cities. Reference [23] categorized the evaluation index system into pollutant treatment and utilization, living environment, economic growth, potential innovation, and ecological efficiency. The authors reported that the treatment of pollutants and utilization was high in the Beijing–Tianjin–Hebei region, but coordination between the cities is less organized. Reference [56] measured the green efficiency of 108 cities in the Yangtze River Economic Belt and found that the GD level of the cities in this region was not high, but the efficiency level showed a trend of gradual improvement in terms of time evolution. A Genuine Progress Indicator (GPI) with sustainability was developed by [57], focusing on the economy, society, and the environment. Other methods documented in the literature for GD evaluation include the entropy method [4,58], the cloud model method [23], and fuzzy set method [59,60]. However, the use of a comprehensive index is common in the assessment of GD [11].

The trade-off between environment and economy is increasingly becoming complex [61]. Based on previous studies, this paper seeks to understand GD in the major cities of Gansu province, China. The super-efficient SBM-model was applied to the collected data to explore the factors influencing GD in Gansu province.

2.5. Financing Green Development

In 2016, the concept of "Green Finance" was discussed extensively at the G20 summit [22]. The importance of green finance in promoting GD is well documented in the literature [36,62]. Financial institutions primarily support GD projects through reasonable credit policies (e.g., interest rate, loan condition) [63]. In Latin America and the Caribbean, [64] reported a USD 110 billion gap in annual financing of climate change-related projects. Through econometric analysis, the authors found that green finance, provided by development banks, is higher in countries with higher human development scores and strong environmental advocacy.

China conceptualized the idea of green finance in the 1990s and it was first implemented by the People's Bank of China in 1995 [22]. China's green financial development negatively affects the general issuance of bank loans but prevents over-investment in renewable energy [22]. The upgrading and restructuring of industries aimed at acquiring novel green funds largely support competitiveness in the market, thereby driving innovations in the economy [36]. The provincial panel analysis conducted by [21] shows that financial development positively impacts water quality with a consequent increase in SO_2 emission. Green finance also drives green building development concerning novel construction, maintenance, and operation of projects [65]. Moreover, green finance potentially improves green technological innovations in industries, promote small and medium-sized enterprises [36], and it is fundamental to improving the structure of energy consumption [66].

2.6. Evaluation Needs of Green Development in Gansu Province

At the regional and national levels, Gansu is an important province in relation to ecological security, economic and social development of China. The province has embraced GD practices since its launch by the Chinese government. However, its level of GD is low [28] and the challenges and prospects of promoting GD in the province have not been researched, much less clarified. Against the backdrop of environmental degradation, resource depletion, and human welfare, the need to evaluate GD status at the micro-level has become important [1]. Bearing this in mind, our research makes the following contributions. The first is related to the expansion of the ideas and extent of GD study by including in-depth analysis of spatial dependence, which is theoretically important and practically significant for GD research at the city or municipal level in China and other regions of the world. The second concerns the suggestion of relevant guidance for policy formulation to aid energy savings and reduce Gansu's carbon emission. Furthermore, each city's trajectories and impacts could enhance the establishment of tailored policies [67] to improve the overall GD of the cities in Gansu, thereby improving the overall Chinese GD. The third is the identification of pathways to establish inter-city collaborative GD strategies to foster a green-based provincial economy in Gansu.

Under this background, this paper takes the cities in Gansu province as the object of study. We aimed to evaluate the GDE of each city to promote green transformation, provide a point of reference for other cities exploring the GD pathway, and suggest policy recommendations that could aid the integration of GD into local development goals in the long-term. To the best of our knowledge, no study has explicitly reported the GD status in Gansu province using city-level data, and our study sought to fill this knowledge gap. Therefore, this paper builds a system of GD evaluation index for Gansu province and examines the differences and convergence of GD in the major cities. The objective is to accurately measure GDE in time and space, clarify the factors affecting GDE in Gansu's major cities, and pin down the spatial association of GDE among the cities. We employ the input–output perspective to evaluate GDE by applying the super-efficient Slack-based measure (SBM). The input involves improvement in the utilization of natural resources and reduction in resource consumption. The output entails the reduced risk of environmental pollution and ecological destruction. Furthermore, we analyzed the GD's spatial autocorrelation in the province and suggested countermeasures to improve the study area's greenery.

3. Research Methodology

3.1. The Study Area

Gansu Province is located in the heart of the northwestern part of China. It is an important water recharge area for the upper reaches of the Yellow River and Yangtze River. It serves as a bridge and link between the Central Plains and Xinjiang, Qinghai, Ningxia, and Inner Mongolia, playing an irreplaceable role in ensuring national ecological security and promoting the prosperity and stable development of the northwestern region. Gansu Province has a vast geographical area with advantages such as relatively rich resources, rich history and culture, and contributes to the Chinese GDP (Table 1). However, the province has a fragile ecological environment, weak infrastructure, industrial competitiveness, poverty, and other outstanding problems that limit economic and social development. In this sense, promoting GD is an effective way to address resource depletion, reduce environmental pollution and achieve economic transformation and upgrading in Gansu province. Therefore, scientific evaluation of GD in the major cities in Gansu province is of great practical significance in supporting Gansu's economic and social development, building the northwest ecological barrier, narrowing the regional development gap and achieving sustainable development.

Table 1. Regional GDP and per capita GDP in Gansu province from 2010 to 2017.

Year	Regional GDP in Gansu Province (10,000 Million Yuan)	Whole Nation GDP (10,000 Million Yuan)	Per Capita GDP (Yuan)
2010	4120.75	401,202	16,113
2011	5020.37	471,563.7	19,595
2012	5650.2	519,322	21,978
2013	6268.01	568,845	24,296
2014	6836.82	636,139	26,433
2015	6790.32	676,707.8	26,165
2016	7200.37	744,127.2	27,643
2017	7459.6	827,122	28,497

3.2. Empirical Analysis

The major studies on efficiency evaluation using multiple decision-making units (DMUs) denote efficiency status by 100%. Therefore, ranking the efficiency of DMUs and analyzing their influencing factors is important for policymaking and the development of improvement strategies. Considering the use of panel data [68] and the exploratory nature of our research, we employed a quantitative approach to examine the objective(s) set forth. First, we compared the GD levels of the major cities in Gansu province by ranking their efficiency values using the super-efficient Slack-based measure (SBM). Second, we explored GD influencing factors using the Malmquist ML index method in the SBM distance function, with the further decomposition of technical efficiency and technological progress. In addition, we calculated input/output redundancy to determine the factors affecting changes in green total factor productivity (GTFP) of the major cities in Gansu [69]. Third, we explored the existence of a spatial correlation between the GDE of the cities under study (through Geographic Information System GIS autocorrelation analysis to determine if there was a spatial spillover of GDE) [55].

3.3. Measurement of Green Development Efficiecny

Green development efficiency (GDE) is essentially a measure of economic efficiency that incorporates environmental factors. Unlike the traditional economic efficiency, GDE measures the economic output of labor, capital and other factor inputs, and also considers the constraints of environmental pollution and resource consumption. Therefore, GDE is defined in this paper as the efficiency value that maximizes social and economic benefits and minimizes environmental pollution where resources are rationally allocated.

Methodologically, research on environmental efficiency evaluation is based on Data Envelopment Analysis (DEA) used to evaluate the complexity of decision units with multiple inputs and output variables [70,71]. Some studies proposed a relaxation variable-based measurement (SBM) approach to evaluate environmental performance because traditional DEA models are radial and may underestimate the ineffectiveness of decision units [72,73]. The SBM model addresses the relaxed variables in production on the one hand and the efficiency in the case of undesired output on the other hand. However, the inherent drawback is that this model's efficiency values can have multiple decision units, sometimes returning a value of 1, making it impossible to evaluate the decision units effectively. On this basis, Tone (2002) proposed the super-efficient slack-based measure (SBM), which can effectively achieve the evaluation and ranking of decision units. This helps to differentiate effective DMUs and enhances the relative comparison of DMUs.The model specification is as follows.

$$\text{Min}\rho = \frac{\frac{1}{m}\sum_{i=1}^{m}\left(\frac{\overline{x}}{x_{ik}}\right)}{\frac{1}{s_1+s_2}\left(\sum_{p=1}^{s_1}\frac{\overline{y^d}}{y^d_{pk}}+\sum_{q=1}^{s_2}\frac{\overline{y^u}}{y^u_{qk}}\right)} \tag{1}$$

$$\begin{cases} \overline{x} \geq \sum\limits_{j=1,\neq k}^{n} x_{ij}\lambda_j;\ \overline{y^d} \leq \sum\limits_{j=1,\neq k}^{n} y^d_{pj}\lambda_j;\ \overline{y^u} \leq \sum\limits_{j=1,\neq k}^{n} y^d_{qj}\lambda_j;\ \overline{x} \geq x_k;\ \overline{y^d} \leq y^d_k;\ \overline{y^u} \leq y^u_k; \\ \lambda_j \geq 0, i = 1,2,\ldots,m;\ j = 1,2,\ldots,n, j \neq 0;\ p = 1,2,\ldots,s_1;\ q = 1,2,\ldots,s_2 \end{cases} \tag{2}$$

The above formula indicates that there are n decision-making units (DMUs). Each decision unit has an input m, the desired output S_1, and an undesired output S_2. x denotes an element in the input matrix, y^d represents an element in the desired output matrix, y^u is an element in the undesired output matrix and λ denotes the coefficient of the corresponding input or output element. ρ is the green development efficiency value and a large ρ value implies high efficiency. Therefore, this study uses the super-efficient Slack-based measure (SBM) with the help of MaxDEA (professional version) software to conduct the empirical analysis [1] aimed at accurately evaluating GDE in the major cities of Gansu province.

Estimation of Green Total Factor Productivity (GTFP)

The ML index potentially compensates because the SBM model's result is static by constructing M (x^t, y^t, x^s, y^s) from time s to time t. It can reflect the changes in inter-period efficiency of technical progress, technical efficiency and green factor total productivity using a mathematical model. In this paper, we examine the causes and trends of GTFP in Gansu province by using the ML index method under the SBM distance function. Furthermore, we decomposed technical progress and technical efficiency. The formula used is as follows:

$$\text{M}\left(x^t, y^t, x^s, y^s\right) = \frac{D^t\left(x^t, y^t\right)}{D^s\left(x^s, y^s\right)} \times \left[\frac{D^s\left(x^t, y^t\right)}{D^s\left(x^s, y^s\right)} \times \frac{D^t\left(x^t, y^t\right)}{D^t\left(x^s, y^s\right)}\right]^{\frac{1}{2}} = EC \times TC \tag{3}$$

where x^t, y^t refer to the input and output vectors in period t, x^s, y^s represent the input and output vectors in period s, D^s (x^s, y^s), D^t (x^t, y^t) denotes the SBM distance functions of the DMU in period s and period t, respectively. The ML index value represents the rate of change of GTFP in the adjacent interval, EC refers to the technical efficiency improvement index, and TC is the technical progress index. When $ML > 1$, $EC > 1$, and $TC > 1$, it implies that GTFP and technical efficiency increases as technology progresses from period t to $t + 1$; when $ML < 1$, $EC < 1$, and $TC < 1$, it means that GTFP and technical efficiency decreases as technology stagnates from period t to $t + 1$.

In this paper, the results of the ML index method under the SBM distance function and further decomposition of technical progress and technical efficiency are used to explore the reasons and trends of green total factor productivity changes in cities in Gansu province.

3.4. Data Sources and Processing

This study used the city-level data of Gansu province retrieved from the China Statistical Yearbook of Cities (2011–2018), China Statistical Yearbook of Urban and Rural Construction (2011–2018) and Gansu Province Statistical yearbook (2011–2018). The cities included in our analyses are Lanzhou, Jiuquan, Jiayuguan, Zhangye, Jinchang, Baiyin, Pingliang, Tianshui, Qingyang, Dingxi, Wuwei, and Longnan. For spatial continuity, the cities with non-uniform time series such as Gannan Tibetan Autonomous Prefecture and Linxia Hui Autonomous Prefecture were excluded from the analysis. Based on the GD measurement model used in this study, there is a need for input and output data (including "good" and "bad" outputs) of the cities under consideration in Gansu Province [1,27]. The selected input variables were capital input, labor input, and energy input (Table 2). The output variables include desired and non-desired outputs. The desired (i.e., good) output was represented by the gross domestic product (GDP) indicator and the non-desired (i.e., bad) output was represented by total SO_2 emission [1,21], industrial wastewater emission [3,4], and industrial smoke. According to the unguided super-efficient SBM model [1,74], the GD level of the major cities in Gansu province from 2010 to 2017 was estimated using MaxDEA software.

Table 2. Description of indicators.

Category	Name of Indicator	Indicator Characterization	Unit
Input indicator	Capital investment	Total fixed asset investment of the whole society	10,000 yuan
	Labor force input	Number of people employed in urban units	10,000
		Private and self-employed persons	10,000
	Energy input	Total social energy consumption	tons
Output indicator	Expected output	Gross regional product	billion yuan
	Undesired output	Industrial wastewater emissions	million tons
		Total SO_2 emissions	million tons
		Industrial smoke (dust) emissions	million tons

3.5. Dynamics of Green Development Efficiency in Gansu Province (2010–2017)

For an in-depth understanding of the differences in the environmental efficiency of the major cities in Gansu province, the Malmquist index of DEA was used to analyze the overall evolution of GDE in the cities under study from 2010 to 2017 [20,27]. Change in GDTFP refers to the impact of technological progress on GD. The change in technical efficiency index refers to the quality of management methods and institutions and decision-making. Change in technological progress depicts various technological advances that are conducive to GD.

3.6. Spatial Patterns of Green Development in Gansu Province

The city-level GDE values of 2010 and 2017 were selected for spatial analysis, to evaluate and visualize spatial GD in Gansu province. We used the GeoDa software to conduct spatial autocorrelation on the GDE index of the major cities in Gansu to obtain a Local Indices of Spatial Autocorrelatio LISA cluster diagram. This approach's significance is the quantitative description of the spatial dependence of the cities on each other.

4. Results

4.1. Analysis Evaluation of Results

The GD of the cities in Gansu province is significant to GD of the northwestern region of China and the country at large. Our results show differences in GDE of the cities under study in Gansu province in 2017 (Table 3). From the highest to lowest, the ranking of the GDE of the cities is Lanzhou, Qingyang, Jinchang, Jiuquan, Tianshui, Zhangye, Wuwei, Jiayuguan, Baiyin, Dingxi, Longnan, and Pingliang. The difference between the GDE of Lanzhou city (i.e., the highest) and Pingliang city (i.e., the lowest) reached 0.85. The range of GDE values recorded by the top three cities (i.e., Lanzhou, Qingyang, Jinchang) was 1.0838 to 1.5109. The GDE in Zhangye, Wuwei, and Jiayuguan city averaged in Gansu province, and the indexes ranged from 0.9091 to 0.9636. The mean GDE of the cities was 0.984, which is less than 1. Overall, five cities had GDE greater than one, while seven cities had GDE values less than one. The seven cities (Zhangye, Wuwei, Jiayuguan, Baiyin, Dingxi, Longnan and Pingliang) with GDE values less than one are designated as inefficient cities. We conducted input redundancy and output deficiency analysis to understand further the reasons for the low GDE of these cities in 2017, and the results are shown in Table 4.

Table 3. Comprehensive evaluation of the green development efficiency of 12 major cities in Gansu province.

City	Efficiency Values for 2017	Ranking
Lanzhou	1.5109	1
Jiayuguan	0.9091	8
Jinchang	1.0838	3
Baiyin	0.8856	9
Tianshui	1.0000	5
Wuwei	0.9575	7
Zhangye	0.9636	6
Pingliang	0.6612	12
Jiuquan	1.0781	4
Qingyang	1.2913	2
Dingxi	0.7712	10
Longnan	0.7029	11
average value	0.9846	

Ranking refers to the ordinal arrangement of green development efficiency of the cities examined from the highest to the lowest.

Table 4. Analysis of input redundancy and output deficiencies of the inefficient cities in Gansu province in 2017.

City	Efficiency Value	Inputs Redundancy			Under Outputs	Over Outputs		
		Capital	Labor	Energy	GDP	Industrial Wastewater Emissions	Industrial SO_2 Emissions	Industrial Smoke (Dust) Emissions
Zhangye	0.9636	25.5342	0.0488	—	—	—	0.4321	0.0473
Wuwei	0.9575	28.4203	−0.4602	—	—	—	0.3484	1.0733
Jiayuguan	0.9091	37.1175	0.1080	—	—	1251.2900	2.6473	4.1266
Baiyin	0.8856	24.5479	4.0643	—	—	—	0.1752	0.3225
Dingxi	0.7712	117.4491	4.9855	—	—	—	0.6662	0.1873
Longnan	0.7029	204.5948	5.1734	—	—	—	0.5929	0.0392
Pingliang	0.6612	237.8684	7.1304	—	—	265.2581	2.3061	0.1345

Inefficient cities generally had redundant capital and labor inputs (Table 4). The highest redundant capital and labor inputs were recorded for Dingxi (117.449, 4.986), Longnan (205.595, 5.173), and Pingliang (237.868, 7.130), respectively. From the perspective of excessive output, there were excessive emissions of industrial sulfur dioxide and industrial smoke (powder) dust pollutants from inefficient cities, especially from Jiayuguan and Pingliang. Similarly, the emission of industrial wastewater was recorded in Jiayuguan and Pingliang cities only.

4.2. *Dynamics of Green Development Efficiency*

The overall GDTFP of the major cities in Gansu Province for all the previous years under consideration was greater than or equal to one (Table 5). Green development total factor productivity showed a decreasing trend from 2011 to 2015 but increased from 2015 to 2017. This trend is consistent with the growth of technological progress and technical efficiency. However, it is noteworthy that the mean values of change in technological progress were higher than those of GDTFP and technical efficiency changes.

Table 5. Dynamics and decomposition of total factor productivity of the overall green development in major cities in Gansu province (2010–2017).

Year	Change in Green Development Total Factor Productivity (GDTFP)	Change in Technical Efficiency	Change in TECHNOLOGICAL Progress
2010–2011	1.0869	1.0103	1.1014
2011–2012	1.0805	1.0254	1.0551
2012–2013	1.0729	0.9921	1.0842
2013–2014	1.0467	0.9794	1.0710
2014–2015	1.0462	1.0022	1.0461
2015–2016	1.1003	0.9681	1.1385
2016–2017	1.2645	1.0453	1.2198

4.3. Spatially Linked Patterns of Green Development in Gansu Province

The result of the analysis of local autocorrelation LISA index can be divided into four: high–high (H-H), which means that the GDE of the region and the surrounding areas are at a high level; high–low (H-L), which means that the GDE of the region is at a high level and those of the neighboring areas are at a low level; low–high (L-H), which means that the GDE of the region is at a low level, but those of the neighboring areas are at a high level; and low–low (L-L), which means that the GDE of the region and the neighboring areas are at a low level.

According to the LISA analysis above, the results show that in 2010, the spatial correlation pattern of GDE of the cities that passed the 1% significance test presented an H-L type of correlation, mainly for Tianshui City. This indicates that the GDE of Tianshui city was high while the neighboring areas had low GDE. The spatial correlation pattern of GDE in the cities that passed the 1% and 5% significance test in 2017 also showed an H-L shape. Specifically, the two cities showing H-L shape are Qingyang and Tianshui, both of which have high GDE, are in the eastern part of Gansu Province and have better ecological quality but weak radiation-driven effects on the surrounding areas. From the spatial correlation analysis, Gansu province's overall GDE is characterized by "high east and low west", and there were spatial differences in the GD of the cities studied (Figure 1).

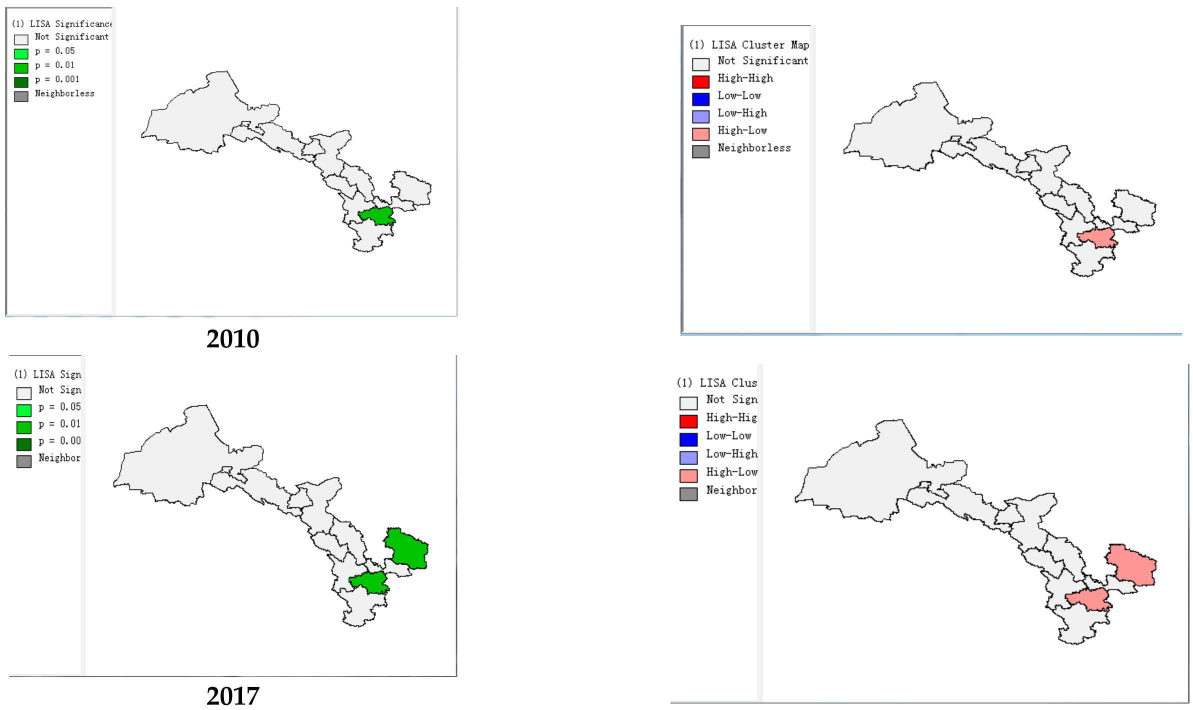

Figure 1. The spatial correlation pattern of GDE in the cities.

5. Discussion

Green development has become an effective means of promoting sustainable development across the world [6,27] through investment in ecological civilization [23], pollution control [1], wastewater management [3], reduction in greenhouse gas GHG emission [21], building technology and innovation [38], and renewable energy resources [22]. In this study, we found differences in the GDE of the major cities in Gansu province. Specifically, the difference between Lanzhou city and Pingliang city, corresponding to the highest and lowest green developed cities, reached 0.85. This finding agrees with earlier reports that the GDE of the cities within the Pearl River Delta (PRD) [4] and Beijing–Tianjin–Hebei region [23], as well as the countries participating in the Belt and Road Initiative [24], differ. Similarly, [2] showed spatial inequality in the green level of private and public spaces in South Africa. The observed difference in the GDE of the cities under study may be attributed to variation in paying attention to ecological protection, economic development, and technological innovation [23].

The average GDE of all the cities considered in this study was 0.985, implying that GD in Gansu province is not yet efficient (<1). However, Gansu's GDE can be improved as indicated in some of the cities (e.g., Lanzhou city). The extent of GD in the top five cities (i.e., Lanzhou, Qingyang, Jinchang, Jiuquan, Tianshui) need to be replicated across the other cities for sustainable development [10]. For Lanzhou city with the highest GDE, the local government should support the GD of related industries while upholding the current development trend. Lanzhou city could serve as the provincial headquarters [10], where GD strategies are formulated, test-run, and spatially circulated to other cities in the province. This approach could advance the GDE in Gansu province to the international standard [4]. For Pingliang city with the lowest GDE, the government should integrate GD into local development goals by reducing pollution emission [12], improve resource utilization [21], and adopt technological innovation [22] to accelerate local economic and industrial upgrading. The local government in other cities should focus on maintaining their advantages and complementing their shortcomings. This is especially important concerning technological efficiency and contributions to technological progress. The GDE in Gansu can provide relevant experience for other cities across China [4].

The availability of green capital and good quality labor within cities can promote GD to facilitate the attainment of a green economy [10]. However, the disparity in the development level in cities could act as a barrier in this regard. This study found that the inefficient cities (GDE < 1) identified generally had redundant capital and labor input. Our result suggests that capital and labor in these cities are not effectively utilized. Whereas the supply of green capital is limited across Chinese cities [4], there is a need for the inefficient cities in Gansu to pay more attention to capital productivity and the rational allocation of labor for improved productivity [65]. This could lead to the emergence of green products that are capable of promoting environmental efficiency and human wellbeing [75]. Against this background, these cities could come up with different GD strategies concerning their industrial foundation and eventually come together under the same umbrella to contribute to GD in Gansu [65].

The "13th Five-Year Plan" of China indicates that paying more attention to environmental indicators is a plausible means of promoting GD [10]. Moreover, the United Nations Agenda for 2030 highlights the importance of environmental indicators as a driver of GD for national development and international cooperation among the countries of the world [1,6]. In this study, excessive Sulphur dioxide and industrial smoke (powder) dust were emitted from inefficient cities, especially from Jiayuguan and Pingliang. The observed difference in the emission of SO_2 and industrial smoke from these cities can be attributed to variation in their resources, economy, population, and environmental conditions. Our results also suggest differences in the capabilities, understanding, and actions taken by these cities in pursuant of GD [76]. Reference [1] shows that the extent of public participation and compliance with government regulation is conducive to promoting GD in China. In this sense, we contend the need for increased awareness about GD, the establishment of public green areas during city development planning [77], and the promulgation of relevant local regulations to aid GD in the cities in Gansu province.

As the economy of China develops, environmental challenges facing the country are on the rise, depicting the idea of substituting economic growth for a green [1] and sustainable environment [78]. A green economy utilizes less water [13] and minimizes pollution through the discharge of wastewater and other forms of pollutants [29]. The discharge of excessive industrial wastewater is prominent in Jiayuguan and Pingliang cities. This result contradicts the findings by [23] who reported that Beijing, Tianjin, and Hebei (BTH) are excellent cities in wastewater treatment and reuse. The difference between the former and present study could be that Jiayuguan and Pingliang cities cannot coordinate the requisite response strategies of handling wastewater compared to BTH [23]. Our result implies that the reuse rate of wastewater needs to be enhanced [4] through the adoption of improved wastewater techniques to reduce the threat to GD in Jiayuguan and Pingliang cities of Gansu [3].

Productivity is an essential factor that enhances economic growth, competitiveness, and the livelihoods of the people living in a country [79]. All the Gansu cities considered in this study had a green development total factor productivity (GDTFP) greater than one. The trend of change in GDTFP is consistent with changes in technological progress and technical efficiency [80]. The mean values of change in GDTFP across the study period (2010–2017) are higher than the corresponding mean value of technical efficiency. This means that the use of new technologies has played a positive role in improving green urban development efficiency in the evaluated cities in Gansu. This finding is in concordance with the report by the authors of [68] that, in a green industry context, technical efficiency and technological progress positively contribute to green total factor productivity. Our result indicates that there is room for improvement in terms of management and decision-making. However, it is worth mentioning that the structure of energy consumption and pollution control can negatively affect GDTFP, as found by [80].

We found spatial differentiation in the GD of the major cities in Gansu in 2010. The spatial association LISA map shows that the cities that passed the 1% significance test formed an H-L agglomeration, particularly for Tianshui city. This implies that the GD in Tianshui city is high, while its surrounding cities are relatively low [6]. Similarly, the cities that passed the 1% significance test in 2017 (i.e., Baiyin Qingyang and Tianshui) formed an H-L agglomeration. Notably, these cities are in the eastern part of Gansu [11] and possess better ecological quality but have a weak effect on their surrounding areas. This implies a stark difference in the GD practices in the "high" and "low" cities, respectively [27,42].

The overall GDE in Gansu depicts a "high-east and low west" pattern. For the "H-L" type spatial correlation pattern, the cities with high GDE should further promote green high-end development while giving due consideration to the GD policies and practices in the surrounding areas. For example, Pingliang city, one of the low GDE areas, should actively refer to the GD policies and practices, ecological safety measures, energy-saving and consumption regulation, and the mechanisms of pollution control in Qingyang and Tianshui city when planning and carrying out governance and ecological remediation projects. This will help to drive a uniform GD in the province.

Implications for Policy

The green economy's attainment through regional integration is currently pivotal to policymaking in Gansu [10,65]. To improve GD's efficiency, policymakers should place more emphasis on effective allocation of resources, strengthen energy conservation, develop pollution emission standards and environmental protection systems. The government should also strengthen the level of awareness about GD [10] because public participation in GD could enhance compliance with the government's regulatory measures to reduce pollution (e.g., Sulphur dioxide) as found by the authors of [1]. The government need to pay attention to the establishment of green financial systems (e.g., green insurance, green development funds) through regulation and policies to further promote GD [22]. Provision of incentives to individuals and enterprises operating within the province could increase the adoption of green development practices [38].

To achieve regional synergistic GD, the local government in each city should appraise the on the ground situation and develop supportive policies to boost GD [4,65]. Under the guidance of a "win-win" GD concept, Gansu cities should engage in inter-city GD cooperation for efficient and harmonious development. The idea of establishing a green development research institute in universities is worthy of consideration [65]. This could help strengthen interdisciplinary research on GD with other disciplines such as agriculture, forestry, and natural sciences. However, this requires increased investment in scientific research of relevant centers of learning [65]. The impact of technological progress on GDE in Gansu is significant. Hence, the government of Gansu province should strengthen the adoption and application of new technologies, optimize the industrial structure, improve on research and development capacity to unravel new green-friendly products, promote industrialization demonstration, and accelerate the transformation of scientific and technological breakthroughs to achieve a sustainable and healthy environment. There may be unforeseen consequences in policy implementation [81]; thus, the government should carry out periodic appraisals and reviews to identify loopholes for possible improvement.

6. Conclusions

This study adopts the super-efficient Slack-based measure (SBM) to comprehensively and dynamically evaluate the green development efficiency (GDE) of the major cities in Gansu province from the input–output perspective. The spatial correlation of GDE was measured by LISA analysis. Overall, the average GDE in Gansu province in 2017 is 0.9846, suggesting that there is room for improvement in this regard. Among the twelve cities included in this study, the cities with GDE values greater than one are Lanzhou, Qingyang, Jinchang, Jiuquan, Tianshui. The seven cities with GDE < 1 generally had redundant labor and capital and excessive emission of SO_2, industrial wastewater, and smoke. The green development total factor productivity had relatively similar growth rates among the cities, driven by technical efficiency and technological progress.

From the LISA analysis, the spatial pattern of green development differs across the cities under study from 2010 to 2017. The cities with high GDE had a weak radiation effect on their surrounding regions. Consequently, the efficient green development technologies and management policies put in place in these green-developed areas are not adequately transferred to their surrounding cities for adoption and implementation.

Gansu's GDE at the city level is extremely unbalanced. The significance of our result is that green development practices such as reduced pollutant emission, the efficiency of labor and capital allocation, and improved natural resource use should be promoted in the province [6] to align with President Xi Jinping's initiative for building a modernized high-quality economy [54]. Our research, covering 2010–2017, extends the report from earlier studies showing that green development efficiency in Gansu is low but follows an increasing trend from 2000 to 2014 (0.243–0.40) [58] and from 2001 to 2015 (0.336–0.482) [30]. Thus, the mean green development efficiency of 0.9846 found in this study is low but indicates an improvement in the green status of Gansu concerning the previous studies.

The green development in Gansu province can provide useful information and practical experience for policymakers and local government officials in other cities in northwestern China and other developing countries. In this regard, we recommend the continuous evaluation of green development in Gansu and other Chinese provinces to track the progress of sustainable development as a consequence of green development. More importantly, advocating for a green-based industry and economy in Gansu could significantly contribute to the overall green development in China.

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