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Re-Estimating China's Cotton Green Production Efficiency with Climate Factors: An Empirical Analysis Using County-Level Panel Data from Xinjiang

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Abstract: Enhancing the green production efficiency of cotton contributes significantly to achieving carbon neutrality and agricultural sustainability. Based on county-level panel data from 2002 to 2020 and daily average temperature and precipitation data from 53 meteorological stations in Xinjiang, this study employs a non-desirable output super-efficiency slacks-based measure model, Malmquist index, and Moran's Index to analyze the temporal and spatial changes in the green production efficiency of cotton across counties in Xinjiang. From a dynamic evolution perspective, without considering non-desirable outputs, the overall cotton production efficiency at the county level exhibits an upward trend; however, when non-desirable outputs are taken into account, the green production efficiency of cotton shows a declining trend, with a general convergence trend among counties (cities). From 2002 to 2020, the overall green production efficiency of cotton in Xinjiang counties decreased from 0.531 to 0.442, with an annual average decline rate of -0.882%. Spatially, as temperatures rise in northern Xinjiang and rainfall increases in the west, high-value areas for cotton green production efficiency have shifted northward and westward, transforming the spatial distribution pattern from "high in the south and low in the north" to "high in the north and low in the south." The spatial clustering effect among counties is significant, exhibiting a "clustered distribution" pattern. To improve the green production efficiency of cotton, it is recommended to promote ecological protection efforts, implement differentiated strategies, leverage spatial clustering effects, disseminate advanced agricultural technologies, and optimize planting structures.

Keywords: climate change, cotton green production efficiency, non-desirable output super-efficiency slacks-based measure model, Malmquist index, Moran's index

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1. Introduction

The 20th National Congress of the Communist Party of China (CPC) proposed to actively address climate change and advance carbon peaking, pollution reduction, afforestation, and economic growth in a coordinated manner, pursuing development that is resource-saving, intensive, green, and low-carbon. This aims to foster harmonious coexistence between humanity and nature and achieve sustainable agricultural development. However, in recent years, the intensification of climate change has introduced many uncertainties into the cotton production process, significantly impacting the sustainable production of cotton [1–3]. As the world's largest consumer and importer of cotton, and the second-largest producer, China's cotton industry plays a crucial role in both national economic development and the global cotton market [4]. Therefore, studying the green production efficiency of cotton under the backdrop of climate change holds significant importance.

Existing studies have demonstrated that cotton production is highly dependent on climatic conditions, and the impacts of climate change on cotton production are primarily reflected in three aspects. Firstly, climate change has led to a northward shift and expansion of areas suitable for cotton cultivation. Research indicates that under the influence of climate change, cotton planting regions

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initially showed a trend of migrating towards the northern Yellow River basin, subsequently expanding further into the northwest region, eventually establishing Xinjiang's dominant position in cotton production [5–8]. Secondly, climate change significantly affects the growth and development cycles of cotton. Under the backdrop of climate change, the growing season for cotton has shown a clear trend of extension. Specifically, there is a tendency for its sowing date, emergence date, squaring date, flowering date, and boll opening date to advance, while the harvest date tends to be delayed [9–12]. Thirdly, climate change will have an impact on water, heat, and other conditions during the growth period of cotton. During its growth and development phases, essential conditions for cotton such as temperature, humidity, light, and CO2 concentration are altered due to climate change, thereby affecting its growth [13–16]. Due to differences in study regions, study periods, and other factors, the academic community has not yet reached a consensus on the direction of the impact of climate change on cotton production, but almost all studies agree that climate change has a significant impact on cotton production.

In the context of the above realities and academic backgrounds, regardless of whether cotton production benefits from or is harmed by climate change, ignoring its impact will lead to biases in the assessment of cotton's green production efficiency. Therefore, when constructing an evaluation index system for cotton's green production efficiency, it is essential to incorporate climate factors—a consideration often overlooked in previous studies.Based on this, this paper integrates daily temperature and precipitation records from meteorological stations with socio-economic datasets to examine the spatiotemporal variations in the green production efficiency of cotton, taking into account the influence of climatic factors. Additionally, given that China joined the World Trade Organization (WTO) in 2001, this study analyzes changes in cotton production from 2002 to 2020 (the latest year covered by the *Xinjiang Statistical Yearbook*), focusing on trends and characteristics following China's accession to the WTO.

2. Materials and Methods

2.1. Study Area

Xinjiang, located in the northwest border region of China and the heart of the Eurasian continent (73°20′E to 96°25′E, 34°15′N to 49°10′N), covers one-sixth of China's total land area, making it the largest of China's provincial-level administrative regions [17] (Figure 1). The region features a complex topography that includes high mountains, basins, rivers, lakes, deserts, Gobi plains, and oases [18]. Xinjiang has a temperate continental arid climate, with an annual average temperature ranging from 6.2°C to 9.0°C and annual precipitation between 93.2 mm and 205.8 mm [19]. It benefits from abundant light and heat resources but suffers from low rainfall and high evaporation rates, making it one of China's most climate-sensitive and ecologically vulnerable areas [20]. Thanks to its unique geographical and climatic conditions, advancements in science and technology, and strong national policy support, Xinjiang achieved remarkable success in cotton production [21]. In 2022, Xinjiang planted cotton on 2.5 million hectares, accounting for 83.2% of the national planting area, with a total output of 5.394 million tons, representing 90.2% of the national total. The yield reached 2,016.0 kg per hectare, the highest in the country. In 2023, the total cotton production was 5.112 million tons, exceeding 90.0% of the national total, establishing Xinjiang's position as China's most important cotton-producing region [22].

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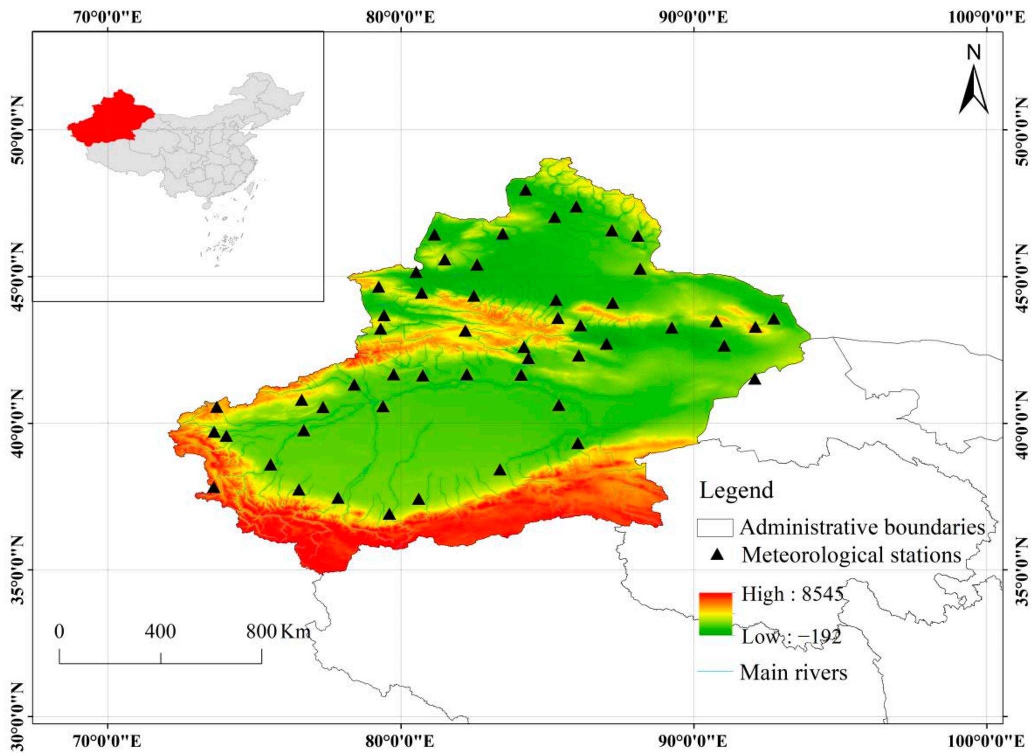

Figure 1. Research area.

2.2. Methods

2.2.1. Undesirable Output Super-Efficiency Slacks-Based Measure Model

The Undesirable Output Super-Efficiency Slacks-Based Measure Model is an advanced Data Envelopment Analysis method used to evaluate the efficiency of multiple decision-making units. Taking into account undesirable outputs, it provides a refined measurement of production efficiency by considering the excess or shortage of inputs and outputs [23]. By introducing the Undesirable Output Super-Efficiency Slacks-Based Measure Model, the purpose is to measure the green production efficiency of cotton in various counties and cities in Xinjiang. The formulas are as follows [24]:

$$\min\rho=\begin{cases}\dfrac{\frac{1}{m}\sum_{i=1}^{m}(\bar{x}/x_{ik})}{\frac{1}{r_1+r_2}\left[\sum_{s=1}^{r_1}\overline{y^d}/y_{sk}^{d}+\sum_{q=1}^{r_2}\overline{y^u}/y_{qk}^{u}\right]}\\ \bar{x}\geq\sum_{j=1,\neq k}^{n}x_{ij}\lambda_j;\ \overline{y^d}\leq\sum_{j=1,\neq k}^{n}y_{sj}^{d}\lambda_j\\ \overline{y^d}\geq\sum_{j=1,\neq k}^{n}y_{qj}^{d}\lambda_j;\ \bar{x}\geq x_k\\ \overline{y^d}\leq y_k^d;\ \overline{y^u}\geq y_k^u;\end{cases}$$

In the formula, $\lambda_j \geq 0$; where i = 1, 2, ..., m; j = 1, 2, ..., n; s = 1, 2, ..., r_1; q = 1, 2, ..., r_2. Here, ρ represents the green production efficiency of cotton; n stands for the number of decision-making units; m represents the inputs; r_1 represents the desirable outputs; r_2 represents the undesirable outputs; x represents the elements in the input matrix; y^d represents the elements in the desirable output matrix; and y^u represents the elements in the undesirable output matrix.

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2.2.2. Malmquist Index

The Malmquist index is a commonly used indicator in economics to measure the dynamic changes in production efficiency, allowing for the calculation of the degree of efficiency change from period *t* to period *t* + 1. By introducing the Malmquist index, the objective is to assess the temporal variations in green production efficiency of cotton [25]. The formulas are as follows:

$$MI = EC * TC$$

$$EC = PEC * SEC = \frac{D_0^{t+1}(x_{t+1}, y_{t+1})}{D_0^t(x_{t+1}, y_{t+1})}$$

$$TC = [\frac{D_0^t(x_{t+1}, y_{t+1})}{D_0^{t+1}(x_{t+1}, y_{t+1})} * \frac{D_0^t(x_t, y_t)}{D_0^{t+1}(x_t, y_t)}]^{1/2}$$

$$PEC = \frac{D_0^t(x_{t+1}, y_{t+1})}{D_0^t(x_t, y_t)}$$

$$SEC = \frac{D_0^t(x_t, y_t) D_0^{t+1}(x_{t+1}, y_{t+1})}{D_0^t(x_t, y_t) D_0^t(x_{t+1}, y_{t+1})}$$

In the formula: (x_t, y_t) represents the input-output vector of cotton green production at period *t*; (x_{t+1}, y_{t+1}) represents the input-output vector of cotton green production at period *t*+1; D_0^t denotes the distance function at period *t*; D_0^{t+1} denotes the distance function at period *t*+1.

MI (Malmquist Index) stands for the Malmquist Productivity Index from period *t* to period *t*+1. A value greater than 1 indicates an increase in productivity; a value equal to 1 indicates no change in productivity; and a value less than 1 indicates a decrease in productivity [26].

TC (Technical Change) represents technological progress or regression; *EC* (Efficiency Change) reflects changes in overall technical efficiency; *PEC* (Pure Efficiency Change) represents changes in pure technical efficiency; and *SEC* (Scale Efficiency Change) reflects changes in the degree of scale. Values greater than 1 indicate an improvement in the indicator compared to the previous stage; values equal to 1 indicate that the indicator remains consistent with the previous stage; and values less than 1 indicate a decrease in the indicator compared to the previous stage [27].

2.2.3. Moran's I

(1) Global Moran's I

The Global Moran's I is a statistical indicator that measures the global spatial autocorrelation of geospatial data. It is used to analyze whether the spatial distribution of cotton green production efficiency across counties (cities) in Xinjiang exhibits clustering, randomness, or uniformity [28]. The formula for calculating the Global Moran's I is as follows:

$$I = \frac{N}{W} \times \frac{\sum_{i=1}^{N} \sum_{j=1}^{N} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{N} (x_i - \bar{x})^2}$$

N represents the number of counties (cities) in Xinjiang; x_i and x_j represent the observed values of the geographical attribute for the ith and jth counties (cities) respectively; $\bar{x}$ is the average value of the geographical attribute for all counties (cities) in Xinjiang; w_{ij} is an element in the spatial weight matrix, reflecting the spatial relationship or proximity between spatial units *i* and *j*; W is the sum of all spatial weights; and I is the value of the Global Moran's I.

If $I > 0$, it indicates a positive spatial correlation, meaning similar values tend to cluster together; if $I < 0$, it indicates a negative spatial correlation, meaning different values tend to be adjacent; if $I = 0$, it indicates that the attribute data is randomly distributed spatially [28].

(2) Local Moran's I

The Local Moran's I serves as a supplement to the Global Moran's I, used to identify the spatial autocorrelation characteristics of cotton green production efficiency across counties (cities) in

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Xinjiang. Specifically, it can pinpoint which specific areas in the data exhibit significant spatial clustering or dispersion patterns. In this paper, the Local Moran's I is employed to identify regions with high values clustering with high values (High-High clusters) and low values clustering with low values (Low-Low clusters) in terms of cotton green production efficiency [29]. The formulas are as follows:

$$I_i = \frac{(x_i - \bar{x})}{S^2} \sum_{j=1}^{N} w_{ij} (x_j - \bar{x})$$

I_i represents the Local Moran's I for the ith spatial unit; S^2 denotes the sample variance; and the meanings of the other symbols are the same as those in the Global Moran's I.

2.3. Indices and Data

2.3.1. Study Period

Since China joined the World Trade Organization (WTO) in 2001, cotton production has undergone a series of adjustments and gradually exhibited more stable patterns of change [30]. Therefore, this study selects 2002 as the starting year for analysis to more accurately observe and evaluate the trends and characteristics of cotton production following China's accession to the WTO. Given that the latest data available in the *Xinjiang Statistical Yearbook* are for 2020, this study ends in 2020.

2.3.2. Input Indices

Climatic Indicators for Cotton Production. Multiple studies have demonstrated that temperature and precipitation significantly influence cotton production [5–16]. This study adopts the method used by Gao, M. to handle climatic variables, selecting temperature and precipitation as the two indicators affecting the green production efficiency of cotton in Xinjiang [31]. Meteorological data are sourced from the China Meteorological Administration (https://www.cma.gov.cn/). The meteorological database includes daily meteorological data recorded by 53 observation stations covering Xinjiang, specifically daily average temperatures and daily precipitation amounts. Following the matching method proposed by Shuai, C [32], this study connects county-level databases with meteorological databases based on the shortest spatial distance between county center coordinates and meteorological station coordinates.

General Input Indicators for Cotton Production. General input indicators typically refer to various input factors related to cotton production or processing, excluding climatic factors. In this study, land, labor, machinery, electricity, and fertilizer are selected as general input variables [31,33–41]. Fertilizer is included while pesticides are excluded from the general input indicators for two main reasons: ①Pesticides and fertilizers play distinct roles in cotton production. Fertilizers primarily provide essential nutrients to plants, directly promoting crop growth and development, whereas pesticides are mainly used to control pests and diseases, protecting crops from damage. ②Pesticide usage data in Xinjiang's statistical yearbooks are not continuous, and their availability and stability are relatively poor. Including pesticides in the input indicator system might negatively impact overall data quality due to discontinuity and volatility. Electricity is included in the general input indicators primarily because of the specific agricultural context in Xinjiang. As a large agricultural region with relatively scarce labor resources, electricity has become an indispensable substitute and supplement in cotton cultivation. Data for general input variables are sourced from the *Xinjiang Statistical Yearbook* (2003-2021), *Xinjiang Statistical Bulletin*, and *China Rural Statistical Yearbook*.

2.3.3. Output Indices

Desirable Outputs. Cotton yield is used as the desirable output. Data on cotton yield are sourced from the *Xinjiang Statistical Yearbook* (2003-2021). Missing values are supplemented using linear interpolation and trend fitting methods. To ensure data quality, counties with more than 10% missing

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values are excluded. This process results in a final dataset of desirable cotton output for Xinjiang from 2002 to 2020.

Undesirable Outputs. In agricultural production processes, the primary factors contributing to carbon emissions primarily include the use of agricultural chemicals and farmland management activities [42]. According to the climate input indicators employed in this study, the main sources of carbon emissions are fertilizer input and land use. Given the limitations of data availability and continuity, this study selects fertilizer application rate as a indicator of carbon emissions from agricultural chemical use, and irrigation area as a proxy indicator for a key aspect of farmland management activities. With reference to the research conducted by Hui, Y and Fawen, Y [42], the carbon emission coefficients for fertilizer application and irrigation area are 0.8956 (kg/kg) and 312.6 (kg/km^2), respectively.

3. Results

3.1. Analysis of Temporal Changes of Cotton Green Production Efficiency

3.1.1. Characteristics of Temporal Variation in Green Production Efficiency of Cotton

(1) Despite an Upward Trend in Cotton Production Efficiency, Green Production Efficiency Exhibited a Downward Trajectory.

As shown in Table 1, despite a sharp increase in Xinjiang's green cotton production efficiency to 0.549 in 2014, which remained relatively stable between 2016 and 2020, the overall trend of green production efficiency from 2002 to 2020 exhibited a downward trajectory. The peak green production efficiency of 0.549 in 2014 represented the highest value recorded over the 19-year period. This notable surge in 2014 coincided with the implementation of the "Cotton Target Price Reform Pilot" policy in Xinjiang. Although primarily aimed at adjusting price mechanisms and securing farmers' incomes, this policy indirectly enhanced green production efficiency by motivating improvements in production efficiency, facilitating adjustments in planting structures, and guiding market orientation. Between 2016 and 2020, the Chinese government actively promoted green agricultural development through various measures, including reducing fertilizer usage, enhancing efficiency, and advancing ecological agriculture, all of which were aimed at fostering sustainable development within the cotton industry. These initiatives indirectly or directly contributed to stabilizing and improving green production efficiency. However, the average green production efficiency for cotton in Xinjiang declined from 0.531 in 2002 to 0.442 in 2020, with an annual average decline rate of -0.882%. The decline can be attributed to farmers' intensive use of chemical fertilizers and other agricultural chemicals in pursuit of higher yields and production efficiency. This practice has resulted in soil degradation and environmental pollution, both of which are detrimental to green cotton production.

Table 1. County-level green production efficiency of cotton from 2002 to 2020.

	2002	2004	2006	2008	2010	2012	2014	2016	2018	2020
Shanshan County	0.134	0.260	0.255	0.270	0.197	0.194	0.204	0.025	0.124	0.105
Toksun County	0.242	1.019	1.005	1.076	1.020	0.329	0.433	0.133	0.209	0.226
Balikun Kazak Autonomous County	0.126	0.071	0.058	0.112	0.123	0.121	0.109	0.006	0.134	0.132
Yiwu County	0.107	0.112	0.085	0.076	0.062	0.088	0.068	0.002	0.097	0.133
Changji City	0.233	0.348	0.401	0.402	0.368	0.495	0.401	0.141	0.420	0.408
Fukang City	0.129	0.152	0.189	0.079	0.081	1.089	1.126	0.007	0.271	0.379
Hutubi County	0.398	0.633	0.537	0.609	0.417	0.478	0.538	0.206	0.684	1.006
Manas County	1.098	1.061	1.009	1.047	1.018	0.773	1.003	0.403	1.002	0.794
Jimusar County	0.093	0.127	0.126	0.069	0.001	0.081	0.058	0.011	0.134	0.111
Chabuchar Xibo Autonomous County	0.135	0.155	0.211	0.341	0.200	0.188	0.108	0.004	0.101	0.107

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Huocheng County	0.131	0.142	0.149	0.116	0.083	0.109	0.104	0.008	0.087	0.109
Wusu City	1.047	1.045	1.130	1.207	1.039	1.020	1.419	1.353	1.863	1.253
Shawan City	0.713	0.654	0.717	0.662	1.006	1.051	1.025	1.068	1.020	1.015
Toli County	0.032	0.096	0.102	0.093	0.115	0.110	0.119	0.010	0.129	0.137
Hoboksar Mongol Autonomous County	0.196	0.308	0.367	0.416	0.471	0.532	0.216	0.096	0.362	0.395
Bole City	0.588	1.001	0.628	0.565	0.492	0.653	0.445	0.455	0.477	0.505
Jinghe County	1.201	1.095	1.081	1.326	1.012	1.159	1.097	1.125	1.049	1.003
Korla City	0.554	1.013	1.041	0.696	1.005	0.838	1.077	1.436	0.750	0.600
Luntai County	0.525	0.595	0.522	0.655	1.019	1.064	1.047	1.001	1.175	1.008
Yuli County	1.896	1.554	1.343	1.477	1.384	1.449	1.289	1.260	1.291	1.477
Ruoqiang County	1.023	1.039	1.023	0.413	0.357	0.271	0.211	0.029	0.156	0.205
Qiemo County	0.759	1.120	1.089	1.651	1.312	1.084	0.487	0.228	0.443	0.331
Yanqi Hui Autonomous County	0.069	0.084	0.109	0.096	0.091	0.142	0.117	0.001	0.090	0.095
Hejing County	0.114	0.170	0.254	0.228	0.302	0.280	0.158	0.000	0.099	0.224
Heshuo County	0.274	0.443	1.013	0.627	0.451	0.468	0.403	0.047	0.248	0.139
Bohu County	0.103	0.168	0.326	0.326	0.248	0.239	0.185	0.035	0.192	0.224
Aksu City	1.028	1.016	0.718	0.815	1.117	1.038	0.706	1.471	0.631	0.702
Wensu County	0.785	0.601	0.644	0.655	0.735	0.690	0.499	1.166	0.415	0.374
Kuche City	0.593	0.662	0.585	0.496	0.516	0.593	0.902	1.192	1.233	0.757
Shaya County	1.030	0.818	1.001	0.752	0.777	0.789	1.057	1.635	1.158	1.457
Xinhe County	1.176	1.034	0.940	1.050	1.379	0.580	1.017	1.112	0.671	0.598
Wushi County	0.177	0.143	0.193	0.279	0.190	0.173	0.092	0.002	0.089	0.140
Awati County	1.009	1.005	0.836	0.709	1.013	1.365	1.386	0.441	0.781	1.045
Keping County	0.213	0.408	0.507	0.481	0.410	0.445	0.559	0.312	0.441	1.010
Atushi City	0.147	0.162	0.186	0.162	0.152	0.145	0.213	0.172	0.195	0.242
Aketao County	0.282	0.308	0.278	0.239	0.180	0.188	0.210	0.057	0.163	0.169
Shufu County	0.289	0.243	0.254	0.230	0.157	0.160	0.273	0.015	0.138	0.163
Shule County	1.018	1.006	0.552	0.395	0.317	0.422	1.308	1.235	0.410	0.475
Yingjisha County	0.204	0.316	0.334	0.298	0.271	0.195	0.331	0.183	0.229	0.279
Zepu County	1.015	0.620	0.538	0.446	0.200	0.202	0.293	0.067	0.161	0.177
Shache County	1.029	0.686	1.285	1.357	0.527	0.462	0.798	0.366	0.293	0.333
Yecheng County	1.045	0.358	0.360	0.389	0.224	0.233	0.414	0.202	0.254	0.290
Makit County	0.847	0.768	1.107	1.022	1.241	0.689	0.857	1.277	0.529	0.448
Yuepuhu County	0.550	0.355	0.497	0.326	0.339	0.335	0.711	0.546	0.547	0.566
Jiashi County	1.025	0.456	0.665	0.564	0.331	0.346	1.038	0.414	0.565	0.502
Bachu County	1.095	1.267	1.080	1.102	1.003	0.662	1.042	0.362	0.555	0.474
Hotan County	0.156	0.236	0.234	0.207	0.191	0.188	0.254	0.089	0.214	0.069
Moyu County	0.148	0.249	0.232	0.216	0.199	0.179	0.211	0.081	0.115	0.093
Pishan County	0.209	0.306	0.297	0.269	0.258	0.206	0.246	0.104	0.115	0.131
Luopu County	0.260	0.298	0.284	0.263	0.213	0.165	0.174	0.009	0.079	0.046
Cele County	0.146	0.236	0.300	0.291	0.263	0.209	0.226	0.036	0.113	0.138
Yutian County	0.194	0.215	0.251	0.339	0.285	0.208	0.264	0.057	0.129	0.160
The average green production efficiency	0.531	0.543	0.556	0.538	0.507	0.484	0.549	0.417	0.439	0.442
The average production efficiency	0.249	0.287	0.331	0.331	0.257	0.282	0.383	0.334	0.295	0.298

(2) Decreasing Disparities in Green Production Efficiency Among Counties (Cities).

From 2002 to 2020, the cotton green production efficiency values in Wusu City, Jinghe County, Yuli County, and Shaya County were all above 1, indicating that these areas were able to maintain high cotton yields while effectively controlling or reducing undesired outputs. In Balikun Kazak

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Autonomous County, Yiwu County, Changji City, Fukang City, Hutubi County, Jimusar County, Shawan City, Toli County, Hoboksar Mongol Autonomous County, Korla City, Luntai County, Yanqi Hui Autonomous County, Hejing County, Bohu County, Kuche City, Awati County, Keping County, Atushi City, Yingjisha County, and Yuepuhu County, the cotton green production efficiency exhibited an upward trend, with Hutubi County, Shawan City, Korla City, Luntai County, and Keping County specifically increasing their cotton green production efficiency values from below 1 to above 1. Conversely, the green production efficiency in Shanshan County, Toksun County, Manas County, Chabuchar Xibo Autonomous County, Huocheng County, Bole City, Ruoqiang County, Qiemo County, Heshuo County, Aksu City, Wensu County, Xinhe County, Wushi County, Aketao County, Shufu County, Shule County, Zepu County, Shache County, Yecheng County, Makit County, Jiashi County, Bachu County, Hotan County, Moyu County, Pishan County, Luopu County, Cele County, and Yutian County showed a downward trend.

3.1.2. Dynamic Analysis of Green Efficiency Changes in Cotton Production in Xinjiang

(1) Instability in the Change of Green Production Efficiency of Cotton.

According to Table 2, from 2002 to 2020, the MI, EC, and TC in Xinjiang were 0.948, 0.969, and 0.994, respectively, all of which were less than 1. This indicates that although the overall performance of cotton production in Xinjiang is close to the optimal state, there is still room for improvement. The value of MI (0.948) indicates that there is still some room for improvement in the average efficiency of cotton production in Xinjiang from 2002 to 2020, that is, it has not reached the optimal state; EC (0.969) indicates that although cotton production in Xinjiang has relatively high technological application, it has not yet reached a fully effective state, reflecting certain resource waste or unrealized technological potential; TC (0.994) is very close to 1, which shows that Xinjiang's cotton production has achieved considerable technological progress, but there is still room for improvement. PEC (1.003) is greater than 1 and greater than SEC (0.969), indicating that during the inspection period, the production unit's performance in improving technology utilization and management efficiency surpassed its ability to adjust production scale for a more optimal scale. The production unit achieved greater efficiency gains through improvements in internal technology and management efficiency. All of the MI, EC, and TC show a fluctuating downward trend, indicating that the development speed of green production efficiency in cotton is slowing down. This slowdown is related to the fragile ecological environment in Xinjiang, and a suitable green development path should be established to alleviate the contradiction between economic development and environmental protection, thus enabling the steady and continuous improvement of green cotton production efficiency.

Table 2. The county-level of Malmquist indices and their decompositions for each year in Xinjiang.

year	MI	TC	EC	PEC	SEC
2003	1.085	1.075	1.010	0.990	1.020
2004	1.168	1.115	1.047	0.996	1.051
2005	0.939	0.991	0.947	1.016	0.932
2006	1.177	1.111	1.060	0.979	1.082
2007	1.065	1.107	0.962	1.197	0.803
2008	0.917	0.952	0.964	0.808	1.193
2009	0.825	0.835	0.988	1.083	0.912
2010	0.900	0.950	0.948	0.951	0.997
2011	1.066	1.084	0.984	1.075	0.915
2012	0.986	1.022	0.964	1.005	0.960
2013	0.889	0.915	0.972	0.944	1.031
2014	1.360	1.221	1.113	1.163	0.957
2015	0.680	0.771	0.882	0.950	0.928
2016	0.733	1.479	0.495	0.915	0.541
2017	0.708	0.572	1.238	1.077	1.150

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2018	0.779	0.862	0.905	0.990	0.914
2019	0.870	0.855	1.017	0.967	1.052
2020	0.925	0.978	0.946	0.940	1.007
Average	0.948	0.994	0.969	1.003	0.969

(2) Divergence in Green Production Efficiency of Cotton Across Various Counties and Cities.

From the perspective of MI, from 2002 to 2020, 19 counties (cities) including Bohu County, Hutubi County, Korla City, Awati County, Yingjisha County, Qiemo County, Luntai County, Changji City, Bachu County, Wusu City, Manas County, Yuepuhu County, Atushi City, Aksu City, Bole City, Shawan City, Kuche City, Wensu County and Pishan County had MI values greater than 1 (Table 3), indicating that these regions have generally achieved positive growth in production efficiency and achieved positive results in agricultural economic development. From the perspective of TC, 26 cities including Awati County, Manas County, Jiashi County, Wusu City, Bachu County, Korla City, Hutubi County, Yuli County, Bohu County, Qiemo County, Aksu City, Bole City, Shaya County, Yuepuhu County, Luntai County, Shache County, Atushi City, Yecheng County, Wensu County, Changji City, Shawan City, Heshuo County, Xinhe County, Shule County, Ruoqiang County, and Keping County have TC values greater than 1, reflecting their significant progress and positive achievements in technological innovation. From the perspective of EC, the EC values of 22 counties (cities) in Bohu County, Yingjisha County, Hutubi County, Pishan County, Korla City, Changji City, Luntai County, Awati County, Qiemo County, Kuche City, Atushi City, Bachu County, Yuepuhu County, Shawan City, Wusu City, Huocheng County, Moyu County, Aksu City, Bole City, Hoboksar Mongol Autonomous County, Hejing County and Manas County were greater than 1. Breaking down the EC, the PEC is generally better than the SEC, indicating that compared to the problem of economies of scale, each county (city) in Xinjiang has more effectively utilized existing resources at the current level of technology.

Table 3. Malmquist indices and their decompositions for cotton in each County (City) of Xinjiang.

	MI	TC	EC	PEC	SEC
Shanshan County	0.945	0.905	0.951	1.136	1.086
Toksun County	1.011	1.109	1.065	1.019	0.868
Balikun Kazak Autonomous County	1.127	1.022	0.971	1.000	0.995
Yiwu County	1.070	0.941	0.994	0.858	0.929
Changji City	1.090	1.054	1.086	1.041	1.014
Fukang City	1.153	0.937	0.981	1.102	0.932
Hutubi County	1.127	1.039	1.120	1.049	1.039
Manas County	1.054	1.072	1.033	1.013	0.998
Jimusar County	0.948	0.864	0.939	1.046	0.813
Chabuchar Xibo Autonomous County	0.977	0.828	0.969	1.003	0.973
Huocheng County	0.993	0.950	0.949	1.056	1.026
Wusu City	1.092	1.036	1.073	1.050	1.014
Shawan City	1.082	1.090	1.021	1.012	1.003
Toli County	1.123	0.989	0.923	0.951	0.878
Hoboksar Mongol Autonomous County	1.139	1.071	0.994	1.006	0.988
Bole City	1.035	1.036	1.010	0.985	1.019
Jinghe County	1.044	1.134	0.948	1.001	0.947
Korla City	1.055	1.039	1.051	1.062	1.020
Luntai County	1.076	1.025	1.058	1.038	1.023
Yuli County	1.008	1.042	0.995	1.012	1.001
Ruoqiang County	0.966	0.988	0.890	1.007	1.018
Qiemo County	0.990	1.038	0.982	1.093	1.028
Yanqi Hui Autonomous County	1.032	0.935	0.892	1.238	1.116
Hejing County	0.991	0.942	1.000	1.072	0.999

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Heshuo County	1.038	1.002	0.964	1.020	1.057
Bohu County	1.158	1.017	1.015	1.092	1.031
Aksu City	1.047	1.034	1.012	1.021	0.989
Wensu County	1.012	1.011	0.995	1.004	0.992
Kuche City	1.090	0.988	1.040	1.041	1.001
Shaya County	1.057	1.023	1.033	0.965	1.077
Xinhe County	1.065	1.018	1.042	0.998	1.026
Wushi County	0.854	0.753	0.851	1.122	0.848
Awati County	1.067	1.045	1.069	1.050	1.021
Keping County	1.067	0.990	1.112	1.047	1.226
Atushi City	1.098	1.065	1.032	1.014	1.024
Aketao County	0.941	1.010	1.047	1.045	1.027
Shufu County	0.847	1.030	0.941	1.032	0.931
Shule County	1.001	1.048	0.967	1.044	1.053
Yingjisha County	0.941	1.071	0.995	1.057	1.032
Zepu County	0.931	1.017	1.009	0.993	1.030
Shache County	0.968	1.066	0.961	1.086	0.986
Yecheng County	0.896	1.056	0.983	1.047	1.023
Makit County	0.862	0.966	0.896	0.966	0.912
Yuepuhu County	0.955	1.048	1.046	1.038	1.023
Jiashi County	0.862	1.033	0.905	0.987	1.014
Bachu County	1.010	1.035	1.046	1.032	0.997
Hotan County	0.995	0.998	0.993	1.056	0.950
Moyu County	0.931	0.980	1.002	1.049	0.955
Pishan County	0.978	0.999	1.004	1.084	1.062
Luopu County	0.743	0.757	0.870	1.124	0.911
Cele County	0.971	0.884	0.956	1.198	1.122
Yutian County	1.029	1.054	0.954	1.167	1.073

3.2. Analysis of Spatial Pattern of Cotton Green Production Efficiency

3.2.1. Overall Spatial Characteristics of Cotton Green Production Efficiency

The ARCGIS software was used to generate spatial distribution maps of cotton green production efficiency. The natural breaks classification method was applied to categorize the efficiency levels into five classes: low efficiency, sub-low efficiency, medium efficiency, sub-high efficiency, and high efficiency. Spatial distribution maps for cotton green production efficiency in Xinjiang counties (cities) were created for six selected time points: 2002, 2006, 2010, 2014, 2018, and 2020 (Figure 2).

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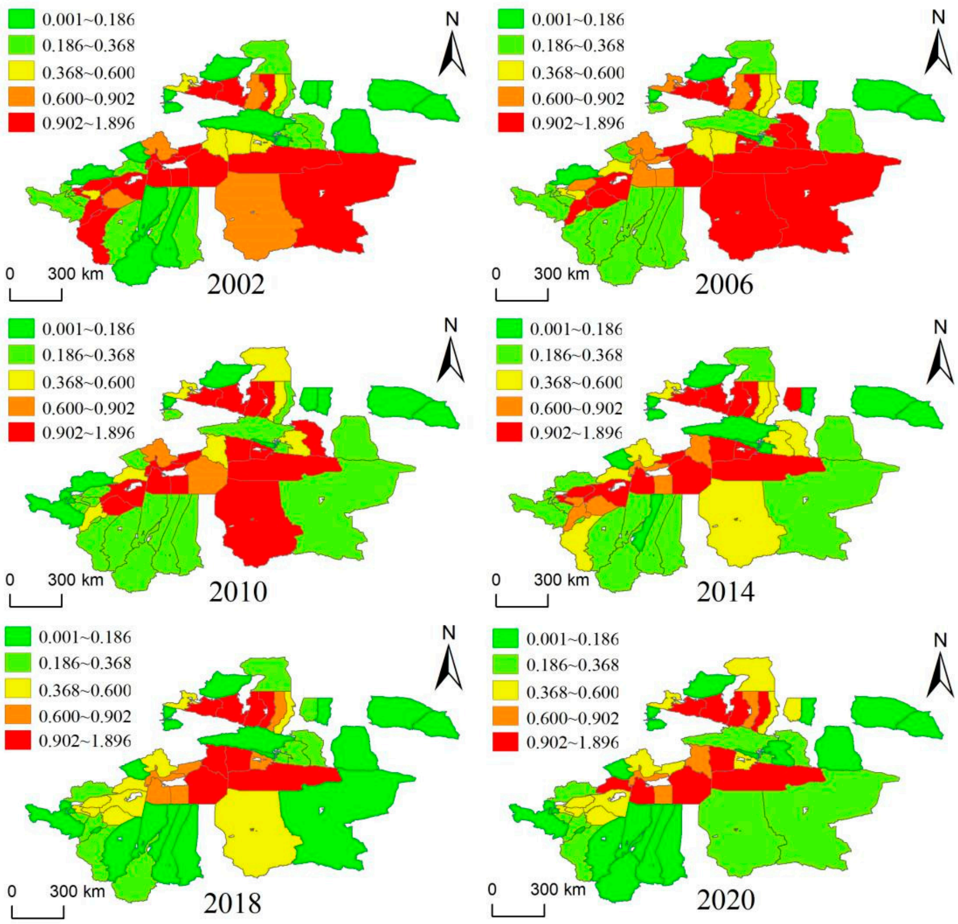

Figure 2. Distribution Map of Green Production Efficiency of Cotton in Counties (Cities) of Xinjiang.

(1) The distribution characteristics of high-value counties (cities) and low-value counties (cities) are apparent.

As can be seen from Figure 2, counties (cities) with high cotton green production efficiency are mainly concentrated in the southern part of Northern Xinjiang and in Southern Xinjiang. The southern region of Northern Xinjiang boasts richer thermal resources necessary for cotton growth compared to its northern counterpart. Southern Xinjiang, characterized by its vast territory and sparse population, boasts large planting areas and a relatively flat and open terrain, which facilitates the operation, circulation, and large-scale management of agricultural machinery, thus contributing to higher cotton green production efficiency. However, Southern Xinjiang is inherently water-scarce. The long-term continuous planting of cotton and excessive use of chemical fertilizers have led to soil salinization, impacting soil health and cotton quality, and consequently reducing green production efficiency.

Low-value cities are primarily clustered in the northern part of Northern Xinjiang, the southern part of Southern Xinjiang, and eastern Xinjiang. In the northern part of Northern Xinjiang, the winters are colder, the spring warming is delayed, and there is a high risk of frost, which not only affects the sowing and growth cycle of cotton but may also shorten the growing season, impacting both yield and quality. Although Southern Xinjiang enjoys abundant sunshine overall, some southern regions face more extreme drought and high temperatures, with extremely scarce water resources and a high degree of dependence on groundwater. The long-term continuous cropping of cotton has caused soil salinization and ecological degradation, affecting green production. In eastern Xinjiang, spring winds and sandstorms are frequent, which is detrimental to seedling preservation. Additionally, the region experiences numerous hot summer days and frequent dry and hot winds, resulting in severe cotton boll shedding. Furthermore, soil and moisture conditions are less ideal compared to other cotton-growing regions, hindering the efficient use of resources[1].

(2) The green production efficiency is gradually transitioning from a pattern of "high in the south and low in the north" to "high in the north and low in the south".

Between 2002 and 2020, Shawan City in Northern Xinjiang improved from sub-high efficiency to high efficiency, while Hutubi County also rose from medium efficiency to high efficiency. Hoboksar Mongol Autonomous County, Changji City, and Fukang City saw improvements from low efficiency, low efficiency, and sub-low efficiency respectively to medium efficiency, demonstrating a trend of high-efficiency cities radiating and driving their surrounding counties (cities) to gradually enhance cotton green production efficiency. In Southern Xinjiang, Aksu City fell from high efficiency to sub-high efficiency; Bachu County, Jiashi County, and Xinhe County declined from high efficiency to medium efficiency; while Yecheng County, Zepu County, Shache County, and Ruoqiang County dropped from high efficiency to sub-low efficiency. Meanwhile, Keping County and Luntai County in Southern Xinjiang rose from medium efficiency to high efficiency; Kuche City improved from medium efficiency to sub-high efficiency; and Hejing County and Bohu County increased from low efficiency to sub-low efficiency. This indicates that while the high-efficiency areas for green production in Southern Xinjiang are contracting towards the north and west, the high-efficiency cities in the northern counties (cities) of Southern Xinjiang are radiating and driving the development of surrounding counties (cities). The dynamic changes in various counties (cities) suggest that as temperatures rise in Northern Xinjiang and rainfall increases in the west, the high-efficiency areas for green production in Xinjiang are also showing a characteristic of shifting northwards and westwards.

3.2.2. Spatial Correlation of Cotton Green Production Efficiency

(1) Global Spatial Autocorrelation Analysis

According to Table 4, the global Moran's I values for cotton green production efficiency in Xinjiang from 2002 to 2020 were all positive, ranging between 0.095 and 0.284, with Z-values greater than 1.055. Except for the years 2012, 2014, and 2015, all other years had passed the significance test. This indicates that the cotton green production efficiency of various counties (cities) in Xinjiang exhibits positive spatial autocorrelation in spatial distribution, meaning that high-value counties (cities) and low-value counties (cities) are geographically adjacent to each other.

Table 4. Moran's I values for green production efficiency of cotton in Counties (Cities) of Xinjiang.

	2002	2003	2004	2005	2006	2007	2008	2009	2010	
Moran's I index	0.162	0.181	0.149	0.217	0.294	0.239	0.251	0.224	0.284	
Z-value	1.970	1.846	1.815	2.215	2.878	2.395	2.519	2.277	2.794	
P-value	0.049	0.065	0.070	0.027	0.004	0.017	0.012	0.023	0.005	
	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Moran's I index	0.249	0.140	0.172	0.095	0.125	0.238	0.229	0.282	0.197	0.190
Z-value	2.508	1.475	1.776	1.055	1.320	2.372	2.302	2.846	2.004	1.948
P-value	0.012	0.140	0.076	0.292	0.187	0.018	0.021	0.004	0.045	0.051

Further analysis reveals that the global Moran's I values for cotton green production efficiency across counties and cities in Xinjiang exhibit a characteristic of initially rising, then declining, and subsequently rising again, indicating that the degree of spatial correlation is unstable. From 2002 to 2010, the global Moran's I increased and reached its maximum value. During this period, modern agricultural technologies and green production practices (such as drip irrigation technology and biological control) were widely adopted across counties and cities in Xinjiang, leading to synergistic

[1] Page 192 of Volume 30 in *General Chronicles of Xinjiang: Agricultural Chronicles*.

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effects among neighboring counties and cities in adopting similar strategies and technologies, and the degree of agglomeration continued to strengthen. From 2010 to 2014, the global Moran's I showed a downward trend and reached its minimum value. Over time, continuous high-intensity production increased ecological and environmental pressures, exacerbated pests and diseases, and led to a continued increase in the use of agricultural chemicals such as fertilizers. This resulted in diminishing marginal benefits of cotton production and increased spatial variability. From 2014 to 2020, Moran's I once again showed an upward trend. During this period, the government vigorously promoted and implemented integrated water and fertilizer management, the substitution of organic fertilizers for chemical fertilizers, and green pest control technologies, which mitigated the contradiction between cotton production and resource exploitation, indirectly or directly promoted sustainable cotton production, increased the positive externalities of cotton green production efficiency, and narrowed the differences in green production efficiency among neighboring counties and cities.

(2) Local Spatial Autocorrelation Analysis

The "high-high" type areas exhibit a cluster of high cotton green production efficiency characterized by "high in the center and high around" (Figure 3). In 2002, the high-high type areas for cotton green production efficiency in Xinjiang were distributed in Kuche City, Yuepuhu County, Shaya County, and Qiemo County. In 2006, they were located in Qiemo County, and Yuli County, showing a trend of northward movement in geographical location for the high-high type areas. By 2010, they were found in Kuche City, Shaya County, and Yuli County, with a notable northwestward shift in the high-high type areas for cotton green production efficiency. In 2014, they were distributed in Kuche City and Yingjisha County. In 2018, they were in Jinghe County, Shawan City, Kuche City, and Xinhe County, marking the first appearance of high-high type areas for cotton green production efficiency in Northern Xinjiang. By 2020, they were located in Kuche City and Xinhe County. In these "high-high" type areas, the large diurnal temperature variation helps cotton accumulate more dry matter, improving the quality and yield of cotton fiber. Despite the relative aridity, the stable irrigation water sources from melting snow and glaciers in high mountains and groundwater ensure the water needed for cotton growth. Under the combined effects of natural conditions, technological advancements, management levels, and policy support, the cotton green production efficiency has developed to a high level.

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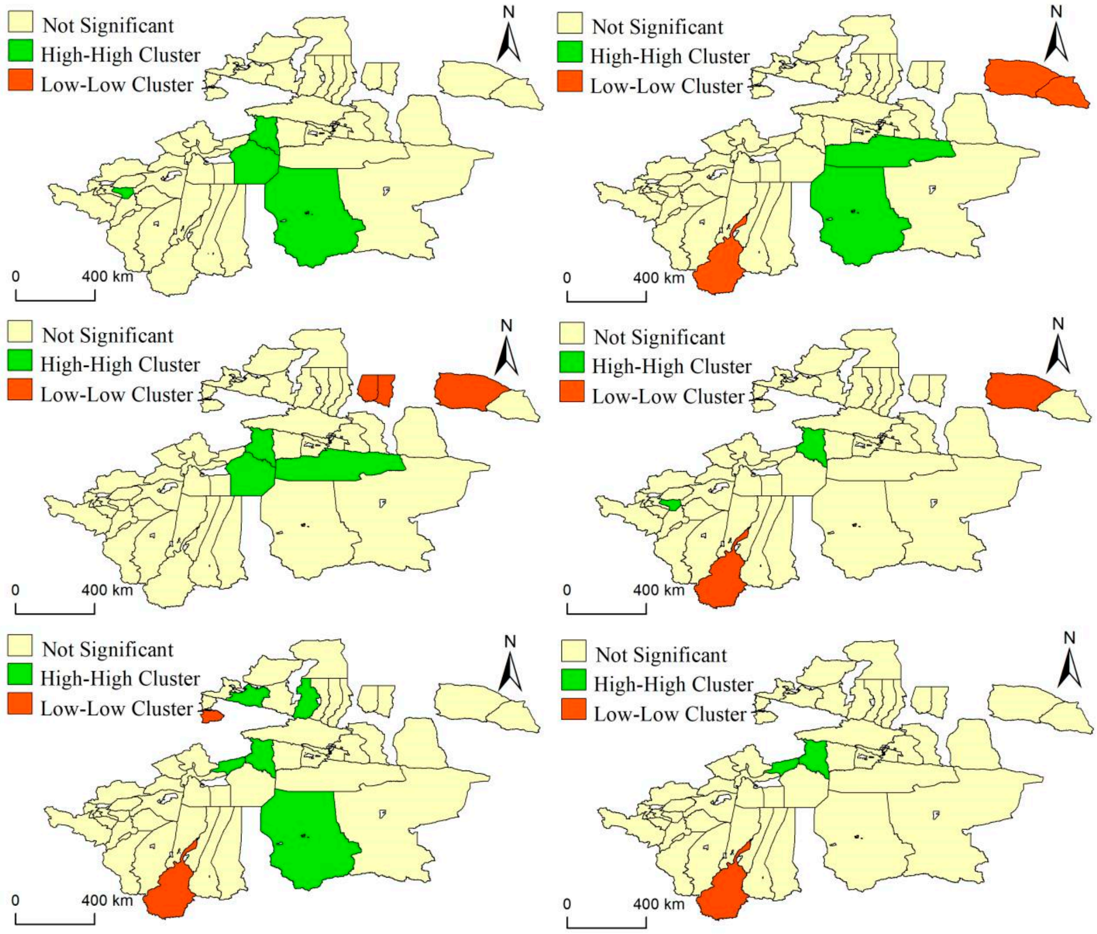

Figure 3. LISA Cluster Map of Green Production Efficiency of Cotton in Counties (Cities) of Xinjiang.

The "low-low" type areas exhibit a cluster of low cotton green production efficiency characterized by "low in the center and low around." In 2002, there were no low-low type areas for cotton green production efficiency in Xinjiang. In 2006, they clustered in Hotan County, Balikun Kazak Autonomous County, and Yiwu County. By 2010, they were distributed in Hotan County, Fukang City, and Balikun Kazak Autonomous County. In 2014, they clustered again in Hotan County and Balikun Kazak Autonomous County. In 2018, they were distributed in Hotan County and Chabuchar Xibo Autonomous County. By 2020, they remained concentrated in Hotan County.

4. Conclusions and Suggestions

This section is not mandatory but can be added to the manuscript if the discussion is unusually long or complex.

4.1. Conclusions

This study employs a non-desirable output super-efficiency Slack-Based Measure model to measure the green production efficiency of cotton at the county level in Xinjiang, incorporating climate factors. The following conclusions are drawn:

From a temporal perspective, despite a sharp increase in Xinjiang's green cotton production efficiency to 0.549 in 2014, which remained relatively stable between 2016 and 2020, the overall trend of green production efficiency from 2002 to 2020 exhibited a downward trajectory. the MI (Malmquist Index), EC (Efficiency Change), and TC (Technical Change) in Xinjiang were 0.948, 0.969, and 0.994, respectively, all of which were trending downwards. When decomposing the EC (Efficiency Change), it was found that PEC (Pure Efficiency Change) generally outperformed SEC (Scale Efficiency Change). Many counties (cities) in Xinjiang have effectively utilized existing resources under current

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technology levels, but attention must be paid to addressing issues related to economies of scale to achieve greater improvements in green production efficiency.

From a spatial perspective, the green production efficiency of cotton in Xinjiang counties (cities) primarily concentrated in southern North Xinjiang and the South Xinjiang region. With rising temperatures in northern Xinjiang and increased rainfall in the west, high-efficiency areas for green production efficiency have shown a trend of shifting northward and westward, transforming the spatial distribution from "high in the south and low in the north" to "high in the north and low in the south". From a holistic perspective, both high-efficiency and low-efficiency counties (cities) exhibit adjacent spatial distributions, but the degree of spatial correlation is unstable, showing a pattern of first increasing, then decreasing, and increasing again. Locally, high-efficiency clusters tend to migrate northward and westward, while low-efficiency clusters mainly concentrate around Hotan County in South Xinjiang and Balikun Kazak Autonomous County in East Xinjiang. Overall, the green production efficiency of cotton shows a "cluster distribution" pattern.

4.2. Suggestions

Based on the aforementioned research conclusions, this paper proposes the following policy recommendations:

(1) Promote ecological conservation efforts to achieve concurrent green and high-quality development.

Firstly, adhere to ecological compensation and restoration. To address potential ecological and environmental issues arising from the expansion of cotton cultivation, such as land degradation and water scarcity, implement an ecological compensation mechanism to encourage farmers to participate in ecological conservation projects. Meanwhile, strengthen the restoration of already damaged ecosystems. Secondly, enhance awareness of ecological and environmental protection. Raise awareness throughout the entire industry chain regarding green production, starting from reducing waste generation and encouraging the cultivation of organic cotton, to build a green supply chain. Thirdly, provide policy support and incentive mechanisms. Offer incentives such as subsidies for technological upgrading to encourage enterprises and farmers to invest in green production technologies and equipment. Additionally, establish and improve a certification system for green agricultural products to enhance market recognition and added value of green cotton products.

(2) Promote advanced agricultural technologies to optimize planting structures and scales.

Firstly, promote advanced agricultural technologies. Given the good performance in pure technical efficiency, further increase the application of modern technology in cotton cultivation, such as intelligent irrigation systems, precision fertilization techniques, and biological pest control, to improve resource utilization efficiency, reduce the use of chemical fertilizers and pesticides, and minimize environmental impact. Secondly, optimize planting structures and scales. Through scientific planning, rationally adjust planting structures and scales to achieve a balance between economies of scale and environmental protection. Further leverage the advantages of new agricultural business entities such as cooperatives and family farms to enhance organizational level, share resources, and reduce costs.

(3) Implement differentiated strategy allocation to achieve precise governance.

Firstly, formulate differentiated green development strategies based on the natural conditions, technological foundations, and production efficiency characteristics of different regions. For the northern Xinjiang region, the focus is on consolidating and expanding technological advantages, continuing to promote technological innovation and application, such as smart agriculture and water-saving irrigation, while strengthening environmental protection measures to ensure sustained and efficient green production. For the southern Xinjiang region, it is necessary to increase investment in infrastructure and technology introduction to improve local technological levels, particularly in soil improvement and water resource management. Secondly, advance the process of precise management. Utilize information technologies such as big data and cloud computing to conduct detailed analyses of soil, climate, and water resources for cotton cultivation in various regions,

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formulate targeted planting plans and management measures, optimize the input of production materials such as fertilizers, and reduce resource waste and environmental pollution.

(4) Leverage spatial agglomeration effects to promote coordinated development across the entire region.

Firstly, optimize industrial layout. Based on the natural conditions and resource advantages of various regions, scientifically plan cotton cultivation areas to form an industrial layout with distinct characteristics and complementary advantages. Concentrate on developing cotton cultivation in suitable areas to achieve scale and intensive management, improving resource use efficiency and green production efficiency. Secondly, establish green production demonstration parks. Set up green production demonstration parks in areas with higher green production efficiency and a good technological foundation to showcase advanced green production models and successful cases, providing replicable and scalable experiences for surrounding regions. Thirdly, build regional cooperation platforms. Promote the establishment of cross-county (city) cooperation alliances for green cotton production, sharing resources, technologies, information, and markets. Through regional collaboration, form a joint force to jointly promote the research and application of green production technologies, achieving rapid dissemination and large-scale application of technological achievements.

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