Spatial and Temporal Evolution of the Eco-Efficiency of Cultivated Land Use in the Region around Beijing-Tianjin Based on the Super-EBM Model

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Article

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Abstract: The eco-efficiency of cultivated land use (ECLU) is an important indicator for the construction of ecological civilization in China. Exploring the spatiotemporal dynamic evolution of the ECLU is helpful for sustainable use of arable land, ensuring food security and ecological security. However, previous studies have mostly focused on the use of a slacks-based measure (SBM) model for ECLU measurement, ignoring the more accurate epsilon-based measure (EBM) model. Therefore, in this study, firstly, we explored the conceptual framework of ECLU, and then, based on the panel data of the counties in the region around Beijing and Tianjin from 2005 to 2020, we investigated the spatial and temporal evolution of ECLU by using the Super-EBM model, kernel density estimation method, and spatial Markov chain model. Results displayed: (1) From 2005 to 2020, the ECLU in the region around Beijing and Tianjin displayed an increasing state, but the average value was only 0.55. (2) The time evolution of the ECLU has gradually polarized, the internal gap has widened, but it tends to stabilize. (3) The ECLU in the region around Beijing-Tianjin was more inclined to keep it the same and there was a "club convergence" phenomenon, which was meaningfully affected by the background of neighboring areas. In the light of local conditions, the government should reasonably formulate the path to optimize the ECLU, strengthen the linkage with the surrounding cities, and bring into play the positive spillover effect.

Keywords: eco-efficiency of cultivated land use; super-EBM model; spatial-temporal evolution; The region around Beijing-Tianjin

1. Introduction

China's agriculture has developed rapidly from the reform and opening-up policy until now, and as the high speed of national economic operation and the rapid growth of industrialization and urbanization, cultivated land use has produced products and services that are beneficial to the production and life of human society, while accompanied by the non-agriculturalization of cultivated land and the phenomena of abandonment, abandonment and inefficient and rough use of cultivated land [1,2]. Besides, the high input and high consumption production model has led to ecological problems such as environmental degradation with "undesired output" [3], which will affect the sound development of farming and national grain security in China in the long run. The No. 1 Central Government Document in 2023 put forward that we should boost the green advancement in agriculture and stimulate the popularization and use of the technology of reducing agricultural inputs and increasing efficiency. Therefore, taking into account the comprehensive development of "resources economy ecology", maximizing expected output and minimizing unexpected output, so

as to enhance the ecological efficiency of the use of arable land, has become a key task for the comprehensive preservation of cultivated land in China.

In the 1990s, German researcher Schaltegger and Stum [4] first came up with the notion of eco-efficiency, which is defined as the proportion of the added value of a product to the environmental impact it brings, emphasizing the coexistence of economy and ecology. In 1996, this concept was further deepened, and World Business Council for Sustainable Development (WBCSD) reputed that it is a competitive pricing of goods or services that provide demand and enhance the quality of livelihood for humanity, while cutting down environmental and resource consumption to meet the land carrying capacity [5]. This notion effectively addressing the issue of economic and ecological coexistence, so it is gradually applied to industry [6], business [7], tourism [8], and agriculture [9] and other fields.

Eco-efficiency, as a notable index, can judge the construction of ecological civilization, reflects the state of coordination between resource use and environment, but it is still essential to attach importance to the research on the ECLU. There are a lot of ways to assess the ECLU, such as ratio method, ecological footprint, environmental sustainability value (ESV), life cycle accounting (LCA), data envelopment analysis (DEA) and stochastic frontier analysis (SFA) [10]. Among them, the latter two methods are frequently applied. Compared to the specific parametric SFA methods, non-parametric DEA does not require allocating functional forms or handling multiple input and output channels [11]. Besides, to address the boundedness of traditional DEA, Tone in 2001 came up with SBM model based on a non-radial relaxation measure, which averts the issue of biased estimation of DEA models and effectively address the slack in traditional DEA with excess inputs and insufficient outputs [12]. In 2004, Tone extended SBM by considering the production efficiency and unexpected output, making the results more realistic [13]. While the proportion of input or output target values obtained from the non-radial SBM model does not match the true value. So, in 2010, Tone proposed the EBM model, effectively addressing the shortage of DEA and SBM models [14].

In current literature, for the study scale, studies on the ECLU have been conducted by scholars at the provincial [15], municipal [16], county [17], and village scales [18]. From the perspective of research regions, the major grain producing areas have been studied by numerous researchers, for example, Yangtze River basin and the black soil area in northeast China have been taken as research areas to explore the ECLU [19,20]. From the perspective of study contents, researchers have taken care of the construction of eco-efficiency index systems and analysis of interfering factors. In terms of constructing the indicator system, the existing literature mostly takes the area of grain sown, the amounts of person employed in agriculture, the total power of agricultural machinery, the amount of fertilizer, pesticide and film use, and the effective irrigation area as input indexes, the agricultural output value and total grain output as desirable outputs, and carbon emissions as undesirable outputs [21,22], however, little consideration has been given to the comparability of indicators across regions. From the perspective of influencing factors, attention has been paid to the endowment of cultivated land resource, society economy development, and agricultural production technology in literature, based on spatial measurement model [23], Tobit model [24]. There are also scholars in the research content of the regional differences in the ECLU, but scholars mostly use spatial autocorrelation to explore the changes in the ECLU [25], however, that cannot describe the process of the transfer and change of the ECLU. How the changes in the ECLU spatially affect the changes of the city around it, which is yet to be explored.

The region around Beijing and Tianjin is located in Hebei Province, neighboring Beijing and Tianjin. Beijing and Tianjin, as municipalities directly under the central government, are significantly urbanized and have large populations. However, the development of urbanization has led to an increase in the pressure on the carrying capacity of the population and a decrease in the amount of arable land, which is a serious threat to local food security [26]. Hebei Province is one of the main grain producing areas in China, rich in arable land resources, and the region around Beijing and Tianjin, as a part of it, has a very important role to play for the coordinated development of Beijing-Tianjin-Hebei, as it has to guarantee the food security of Beijing and Tianjin while guaranteeing the self-sufficiency of grain. Therefore, there is a need to urgently understand the status of arable land

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use in the region around Beijing and Tianjin to guarantee the sustainable use of arable land and food security. The main purpose of this article, using the region around Beijing-Tianjin as an example, is to: (1) to reflect the ECLU of unit area and to compare the ECLU between research units, in terms of indicator selection, establishing an indicator system for land average variables; (2) to measure the ECLU accurately, the research method adopts the Super-EBM model to calculate the ECLU; (3) to describe the dynamic evolution characteristics of the ECLU, in terms of research content, using kernel density estimation and spatial Markov chain models to explore the spatiotemporal differentiation of the ECLU; (4) to provide policy recommendations based on research findings. The aim of this paper is to investigate the evolutionary mechanism of the ECLU in the region around Beijing-Tianjin, with a view to promoting the sustainable development of cropland in the region and guaranteeing food security in the study area and Beijing-Tianjin.

2. Study Area and Data Sources

2.1. Study Area

The region around Beijing and Tianjin is adjacent to Beijing and Tianjin, is situated in the north-central part of Hebei Province, one of the ten major grain producing areas in China, including six prefecture-level cities, Zhangjiakou, Chengde, Tangshan, Langfang, Baoding, and Cangzhou. The total land area is 133,000 km^2, occupying for 70.4% of Hebei Province. The cultivated land area is 0.23 ha/person, and the agricultural population is 15.52 million, accounting for 51.77% of the total population. According to the national standard of cultivated land quality, the quality of arable of the region around Beijing-Tianjin is at the medium level, and the soil types are mainly chestnut-calcium soil, brown loamy brown soil, brown soil, semi-arid and saline tidal soil, and the main crops are wheat and corn. The landform types from northwest to southeast are coastal mud flats, plains, hills, mountains, plateaus, etc. As an important part of Beijing-Tianjin-Hebei, the region around Beijing-Tianjin plays a prominent part in ensuring food safety in Beijing-Tianjin. There are 71 counties (cities and districts) which are used as the study units in this paper (Figure 1).

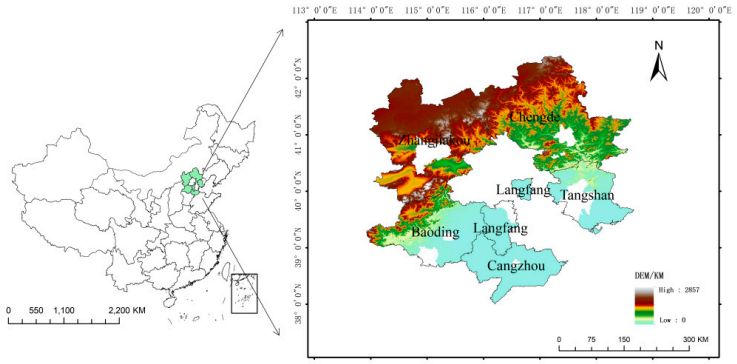

Figure 1. Overview map of the region around Beijing-Tianjin

2.2 Data Sources

The Hebei Rural Statistical Yearbook and Hebei Statistical Yearbook provided us with data from 2006 to 2021. To exclude the effect of prices, according to the consumer price index for rural residents, the value added of agriculture is converted to 2005 constant prices.

3. Research Methodology

3.1. Connotation of the ECLU

Eco-efficiency implies both economic and ecological meanings. The WBCSD [5] and the World Organization for Economic Cooperation and Development (OECD) [27] discussed the definition of eco-efficiency. Meanwhile, it was mentioned in human-earth systems that when human economic

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and social systems are in moderate coupling with natural ecosystems, the system will develop toward positive succession and coordination, otherwise the system degrades or declines [28]. This concept emphasizes the harmonious development of economy, society and ecology (man and nature). Thus, this paper defines the ECLU as a high degree of harmonization of the outputs of both socio-economic and environmental systems per unit of arable land with the minimum input of production factors by human beings, i.e., the right amount of production factors are invested in the procedure of cultivated land use, the agricultural added value and grain per unit of cultivated land output are maximized, carbon emission per unit of cultivated land is minimized and the "resource-socio-economic-ecological" coordinated development is finally achieved. The ultimate goal is to achieve "resource-socio-economic-ecological" coordinated development and symbiosis between human and nature (Figure 2).

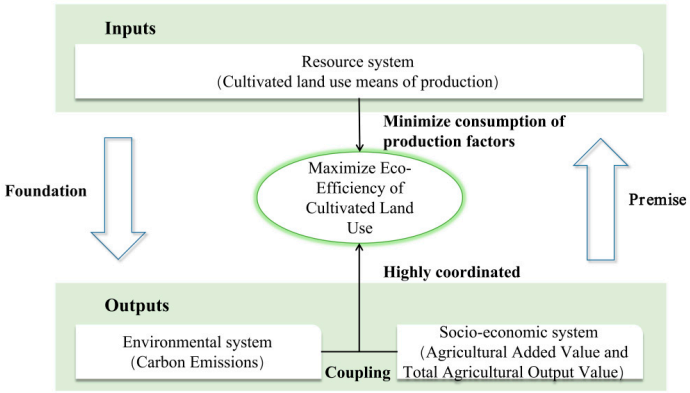

Figure 2. Map of the connotation mechanism of the ECLU.

3.2. Index System Construction

According to the existing research results [29,30], based on the actual situation of cultivated land use in the region around Beijing and Tianjin, in order to reflex the comprehensive needs of resource savings, stable economic and social growth, and preservation of environment, the ECLU quota is as bellow (Table 1).

Table 1. Table of evaluation index system of the ECLU.

Indicator	Variable	Unit	Calculation method
Inputs	The average number of agricultural machinery power	kw/ha	Total power of agricultural machinery/crop sown area
	Average number of people employed in primary industry	person/ha	Number of people employed in primary industry/crop sown area
	The average amount of fertilizer used on the land	t/ha	Fertilizer use / crop sown area
	Local average use of pesticides	t/ha	Amount of pesticides used/crop sown area
	Local average use of agricultural film	t/ha	Amount of agricultural film used/crop sown area
Desirable output	Local average agricultural value added	10^4 yuan/ha	Value added of agriculture/crop sown area
	Local average food production	t/ha	Total food production/crop sown area
Undesirable output	Local average carbon emissions	t/ha	Carbon emissions/crop sown area

According to the existing finding [31], the carbon emissions from arable use were calculated as bellow:

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$$E = \sum E_i = \sum T_i \times \delta_i \tag{1}$$

Where E is the carbon emission; E_i is the carbon emission of carbon source; T_i is the amount of carbon source; δ_i is the carbon emission coefficient. In the light of the data of Oak Ridge National Laboratory and the United Nations Intergovernmental Panel on Climate Change, the carbon emission coefficient of tillage is 312.6 kg/km^2, the carbon emission coefficient of total power of agricultural machinery is 0.18 kg/kw, and the carbon emission coefficient of fertilizer is 0.8956 kg/kg, the carbon emission coefficient of pesticide is 4.9341 kg/kg, and the carbon emission coefficient of film is 5.18 kg/kg.

3.3. Super-EBM Model

Tone [14] tendered the Super-EBM model, which considers both relaxation variables and the proportion of the obtained actual value to the target value. In this article, using the Super-EBM model to assess the ECLU in the region around Beijing-Tianjin, and the formula is as bellow:

$$\gamma^* = \min\{(\theta - \epsilon^- \sum_{i=1}^{m} w_i^- s_i^- / x_{i0}) / [\phi + \epsilon^+ (\sum_{r=1}^{s} w_r^+ s_r^+ / y_{r0} + \sum_{p=1}^{q} w_p^{u^-} s_p^{u^-} / u_{p0})]\} \tag{2}$$

$$\text{s.t.} \sum_{j=1}^{n} x_{ij}\lambda_j + s_i^- = \theta x_{i0} \tag{3}$$

$$\sum_{j=1}^{n} y_{rj}\lambda_j - s_r^+ = \phi y_{r0} \tag{4}$$

$$\sum_{j=1}^{n} u_{pj}\lambda_j + s_p^{u^-} = \phi u_{p0} \tag{5}$$

$$\lambda_j \geq 0,\ s_i^-, s_r^+, s_p^{u^-} \geq 0 \tag{6}$$

Where γ^* ($0 \leq \gamma^* \leq 1$) is the optimal efficiency value; λ_j refers to the linear combination coefficient of DMU0; x_{i0}, y_{r0}, u_{p0} and s_i^- is DMU_0 input, expected output, undesirable output and DMU_0 input relaxation, respectively; n, m, s, q stand for number of DMU_0, inputs, desirable outputs, and undesirable outputs, respectively; $s_r^+, s_p^{u^-}$ is the desirable and undesirable output relaxation. $w_i^-, w_r^+, w_p^{u^-}$ are the importance of various indicators' inputs, desirable outputs and undesirable outputs. θ and ϕ is the radial programming parameters; ϵ is the kernel parameter of the importance of the non-radial part, which satisfies $0 \leq \epsilon \leq 1$.

3.4. Kernel Density Estimation

Kernel Density Estimation (KDE) is a nonparametric method, which is evaluated the density of probability of random variables and reflect the distribution state of things. This paper uses the kernel density estimation method to analyze the time evolution of the ECLU in the region around Beijing and Tianjin, and its functional expression is:

$$f(x) = (1/Nh) \sum_{i=1}^{N} K[(x_i - \bar{x})/h] \tag{7}$$

Where f(x) is the density function of the ECLU; x_i is the observed value of the ECLU in each county, $\bar{x}$ is the overall efficiency mean; N is sample size; h is the bandwidth; K(·) is the core function.

3.5. Markov Chain Model

For the sake of reflecting the dynamic changes of things, this paper adopts Markov chain model to make specific analysis on the shift trend of things occurring. The traditional Markov chain model divides the ECLU into categories and constructs N×N method for obtaining the dynamic evolution characteristics of the ECLU in the region around Beijing and Tianjin through N-order Markov probability transfer matrix. Assuming that P_{ij} is the transfer probability of the ECLU in a region from i to j, we can estimate the probability of transfer using the frequency of transferring, which is calculated as follows:

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$$P_{ij} = n_{ij}/n_i \tag{8}$$

Where n_{ij} is the number of counties where the ECLU shifted from i to j during the research time; n_i is the number of counties in i.

Based on this, the spatial Markov chain model introduces the notion of spatial lag, which is further considering the impact of spatial correlation of eco-efficiency between regions. In the light of the spatial lag type at the beginning, the traditional N × N order probability transfer matrix is resolved into N N × N order probability transfer matrices, and P_{ij} (N) is the probability that the transfer of the ECLU from type E_i to type E_j occurs when the spatial lag type is N. Where, the spatial lag value is the spatially weighted mean of the ECLU of neighboring counties of county i. The spatial Markov transition matrix can better reveal the mechanism of geographic spatial patterns than the traditional. The formula is as bellow:

$$lag_i = \sum_{i=1}^{n} Y_j W_{ij} \tag{9}$$

Where lag_i is the spatial lagging value of a county; Y_i is the ECLU in a region; n denotes the total number of counties; w_{ij} is the spatial weight matrix, i.e., the spatial adjacency of counties i and j.

4. Results and Analysis

4.1. Results of the Determination of the ECLU Based on the Super-EBM Model

4.1.1. Analysis of Annual Change Features of the ECLU

From Figure 3, the radial Banker–Charnes–Cooper (BCC) model is more efficient than the non-radial SBM model, and the result of the SBM model without considering the internal undesired output is higher than that of the SBM-Undesirable model considering the internal undesirable output, which indicates that the non-radial model can overcome the shortcomings of the radial model, and that not considering the internal undesirable output leads to the overestimation of the eco-efficiency. At the same time, in the case of considering internal undesirable output, the efficiency value of SBM-Undesirable model is smaller than that of EBM model, which indicates that EBM model integrates the advantages of radial and non-radial functions, and it has a better comparative advantage in eco-efficiency measurement. Therefore, this paper adopts a non-directed, scale-reward invariant, Super-EBM model to measure the ECLU in 71 counties in the region around Beijing-Tianjin from 2005 to 2020.

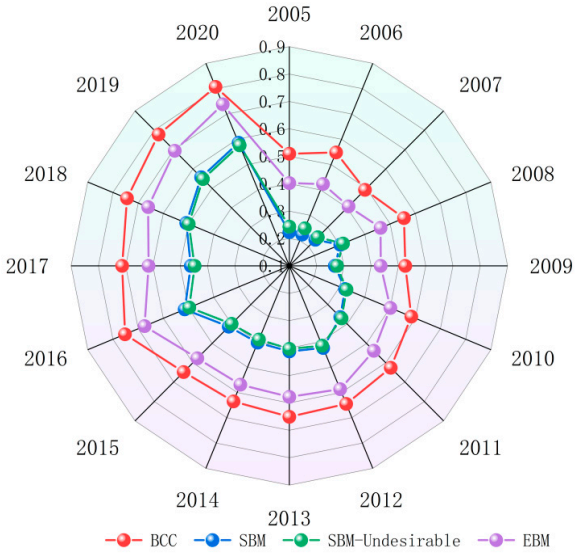

Figure 3. Comparison of the ECLU measured by each model in the region around Beijing-Tianjin.

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As shown in Figure 4, the overall state of the ECLU in the research area from 2005 to 2020 expanded from 0.388 in 2005 to 0.727 in 2020, with a rate of rise of 87.37%, but a sharp decline in 2017, mainly impressed by natural calamities such as abnormally high temperature and low precipitation leading to drought, with an overall average value of only 0.55. The ECLU in the region around Beijing and Tianjin still has much room to rise. In the future process of cultivated land use, more importance needs to be attached to the rational invest and resource use of arable to guarantee the sustainable use of cultivated land.

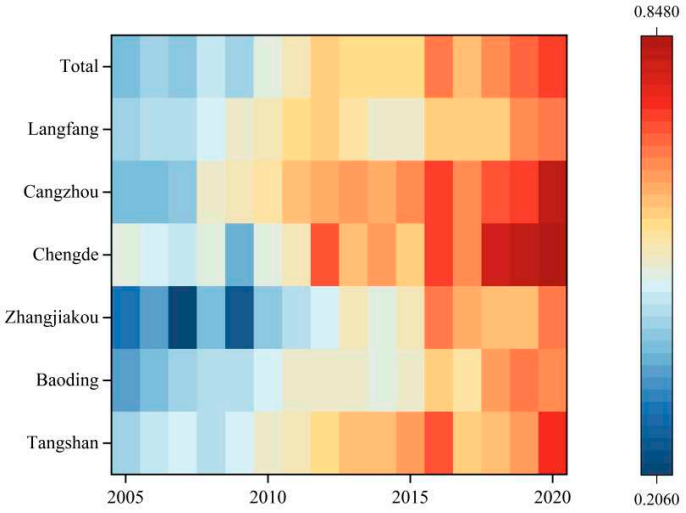

Figure 4. Changes in the ECLU in the region around Beijing and Tianjin as a whole and in each city from 2005 to 2020.

As shown in Figures 4 and 5, the ECLU in the research area is consistent with the overall trend, but there are disparities among the cities, and the disparities is more obvious over time. In the light of the average value, the ECLU in Chengde, Cangzhou and Tangshan was relatively high, 0.609, 0.603 and 0.571, respectively, which is due to the obvious advantages of local transportation location, developed advanced technology, more investment in agricultural machinery, and strong awareness of ecological protection of farmers. And Langfang, which borders Beijing and Tianjin, has the most stable development and is comparable to the overall average in terms of the ECLU, but its unique location advantage has not been fully utilized. Zhangjiakou and Baoding are lower, with the ECLU values of 0.476 and 0.517, mainly because Zhangjiakou and the western part of Baoding are mostly mountainous areas, with poor quality cultivated land and poor agricultural infrastructure. From one year to another, the ECLU of Chengde and Zhangjiakou has changed significantly. The ECLU in Chengde declined significantly in 2009, mainly due to the impact of drought, which led to a 50.2% reduction in grain production and thus a sharp decrease in the ECLU. In 2012, the ECLU value rose sharply, which depended on the total power of agricultural machinery increased by 5.9% compared with the previous year, and agricultural production conditions were greatly improved. The ECLU of Zhangjiakou fluctuated greatly from 2005 to 2010, the main reason for the decline in 2007 was the decrease in agricultural output value, which was 13.3% lower than the previous year, and the significant decrease in 2009 was due to the sudden decrease in grain production caused by the drought.

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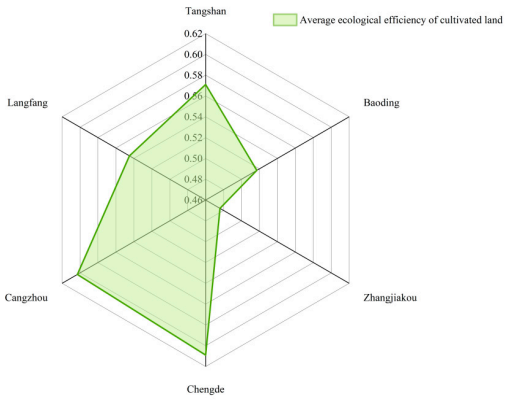

Figure 5. Comparison of the ECLU by cities in the region around Beijing and Tianjin.

As shown in Figure 6, from a county perspective, the average value of eco-efficiency in all counties did not reach an effective state. Relatively speaking, the counties (cities and districts) with overall high ECLU are Rongcheng County of Baoding, Longhua County of Chengde and Pingquan City, Yutian County and Caofeidian District of Tangshan, Dachang Hui Autonomous County of Langfang, Renqiu City, Cang County and Qing County of Cangzhou, with mean efficiency values reaching 0.7 or more, of which 33.33% are in Cangzhou City, followed by Chengde City and Tangshan City, and one county each in Baoding and Langfang. The reason for that is that the high ECLU of the three counties in Cangzhou City is related to their topography and location, as all three counties are in the plain area, and Renqiu City, Cangzhou County, and Qing County are bordered by Xiong'an New Area, Cangzhou City, and Tianjin City, respectively, so they are more likely to be exposed to advanced agricultural farming technology and ideology in comparison. While Rongcheng, which has the highest efficiency mean, is located in Baoding, which was designated as Xiong'an New Area in 2016, and the scale and mechanization of land are constantly improving, and the awareness of environmental protection is advancing with the times to improve the ECLU. However, there are 29 counties with an average efficiency of less than 0.5, including Yangyuan County, Yu County and Quyang County, with 34.48% in Baoding and 24.14% in Zhangjiakou, which are mainly located around the Taihang Mountains, with high terrain, relatively poor soil, and poor agricultural irrigation conditions, so there is greater space.

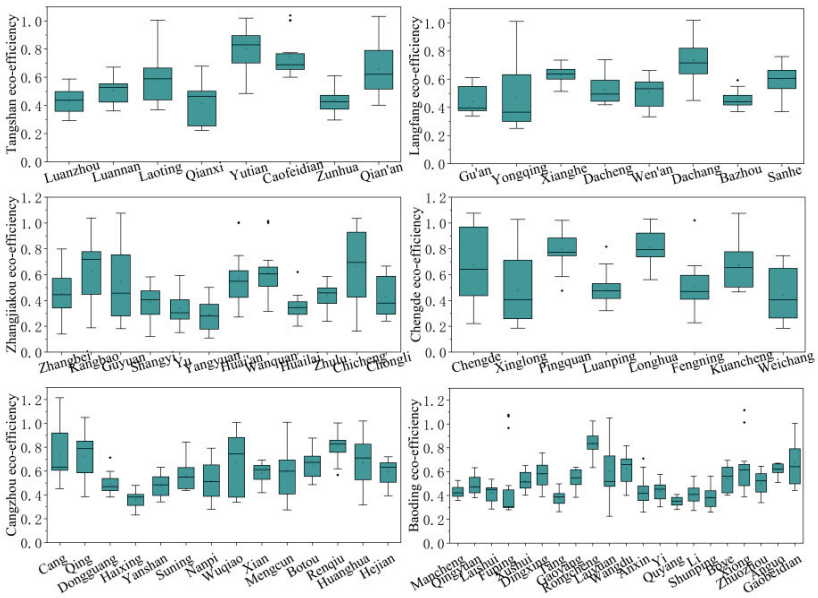

Figure 6. Mean value of the ECLU by counties in the region around Beijing and Tianjin.

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Four periods of the ECLU data in 2005, 2010, 2015, and 2020 in the region around Beijing and Tianjin were selected for analysis, and the data were visualized using ArcGIS 10.7. The natural interruption point method was used and considering that an efficiency of 1 is an effective decision-making unit, each county unit was divided into five classes according to (0, 0.5], (0.5, 0.6], (0.6, 0.7], (0.7, 1.0], and (1.0, 1.1] into five classes, as shown in Figure 7.

Study on the temporal features of the ECLU in each county. In general, the number of zones increased, except the number of inefficiency zones gradually decreased. 59 of 71 counties were in the inefficiency zone in 2005, accounting for 83.1%, but only 2 counties, Longhua County and Caofeidian District, were effective decision-making units, i.e., high efficiency zones, whose percentage was only 2.82%, indicating that the space distribution of efficiency values in the research area was relatively homogeneous at this time, and there is a large potential for development. As the promotion of the construction of ecological civilization, the ECLU in several counties (cities and districts) in the region around Beijing and Tianjin increased to different degrees from 2005 to 2020. 2010 saw a slight improvement in ECLU, but more than two-thirds of the counties were still in the inefficiency zone. In 2015, the ECLU was further improved, and the number of inefficient zones accounted for about one-third, and more than 40% of the areas were medium-high efficiency zones. In 2020, the ECLU has improved significantly, with only 6 counties in the inefficiency zone, mainly in southwest Zhangjiakou, southwest Baoding and eastern Cangzhou, and those 6 counties have been in the low efficiency zone for 16 years, with poor resource endowment being the fundamental reason for their low ECLU. The number of counties in the lower, medium and higher efficiency area are 12, 22 and 18 respectively, but the overall ECLU of the western area of the region around Beijing-Tianjin is low. 13 counties (cities and districts), including Qian'an City, Rongcheng County, Guyuan County, Pingquan City and Cang County, have efficiency values greater than 1, i.e., they are in an effective state, indicating that these 13 counties attach more importance to the rational use of resources and have a stronger sense of ecological protection. While the ECLU values of Longhua County and Caofeidian District have dropped from the high efficiency area in 2005 to the higher efficiency area. The efficiency value decreases significantly, which is mainly due to the increase of redundancy in essential productive factors such as pesticides, films and chemical fertilizers.

4.1.2. Study on the spatial distribution features of the ECLU

From the distribution of the ECLU by county in 2020, the distribution of low and lower efficiency zones is concentrated, mainly distributed in the western part of the region around Beijing and Tianjin with Zhangjiakou City and the western of Baoding City as the main part. Although the ECLU improved during the research time, the growth of the ECLU was slow, which was caused by the barren quality of cultivated land in the area, the high altitude, and the insufficient agricultural water supply. The low ECLU in Yanshan and Haixing counties in the southeastern part of Cangzhou City is mainly due to the extensive distribution of saline land, which leads to the low output rate of cultivated land and thus inhibits the ECLU. The distribution of medium efficiency zones is relatively scattered. The higher efficiency zones and high efficiency zones, although involved in all municipalities, are mainly distributed in Cangzhou in the immediate south of Tianjin and Tangshan in the north, which are mainly related to their location advantages and topographic conditions, which are flat and suitable for large-scale cultivation. And Tianjin, as a municipality directly under the central government, is an important transportation hub, with obvious radiation effects on the surrounding counties, and is in the coastal zone, with relatively advanced production concepts and planting techniques are introduced, so the use of cultivated land is more scientific and rationalized, thus enhancing the ECLU.

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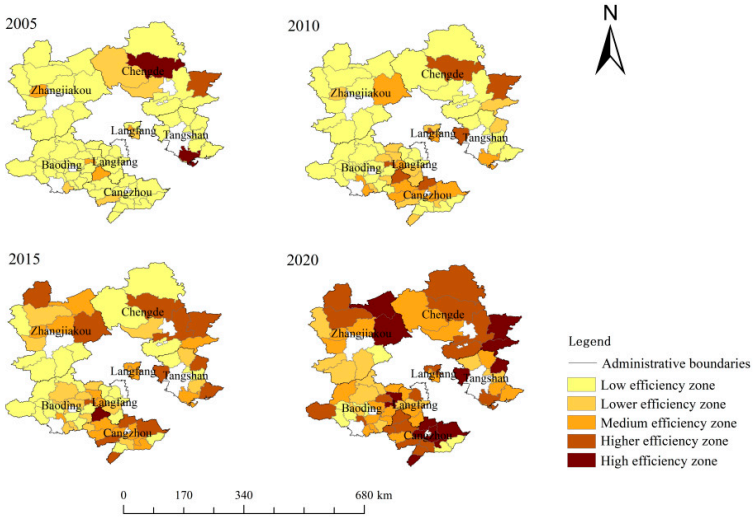

Figure 7. Spatial and temporal variation of the ECLU by counties in the region around Beijing and Tianjin.

4.2. Study on Temporal Evolution Features

Using the kernel density estimation method to analyze the temporal evolution of the ECLU in the region around Beijing and Tianjin from 2005 to 2020, and the outcomes are shown in Figure 8.

From the overall state of its curve, it keeps moving right, indicating that the ECLU in the region around Beijing-Tianjin keeps increasing during the research time. The distance between the curves shows that the efficiency increases at different rates, with the ECLU interval increasing from [0.3, 0.4] to [0.4, 0.5] from 2005-2010, the ECLU value increasing but remaining at [0.4, 0.5] from 2010-2015, and ECLU interval increasing from [0.4, 0.5] to [0.6, 0.7] and approaches 0.7, and the overall efficiency showing a "fast-slow-fast" growth trend.

In terms of shape, the years 2005-2020 all show a "bimodal" pattern, but the "bimodal" pattern is not obvious in 2005-2015, and the pattern is significant in 2020, which indicates that there has been polarization from 2005 to 2020, but significant polarization in 2020. The peak in 2005-2015 has a more obvious downward trend, and the peak in 2015-2020 is of the same height, which implies that the internal gap of the ECLU is expanding but gradually converging to a stable situation. The different resource endowments and socio-economic development have resulted in the differentiation of efficiency among counties in the process of cultivated land use.

From the interval of the nuclear density curve, the left tail keeps shortening, indicating that there is a catching-up effect from counties with lower eco-efficiency to higher counties, and the right tail value initially decreases, but later continues to increase, impling that high-efficiency counties increase, and the overall ECLU development momentum is better. Although the gap between counties in terms of the ECLU gradually expands, most counties show an increasing trend in efficiency values.

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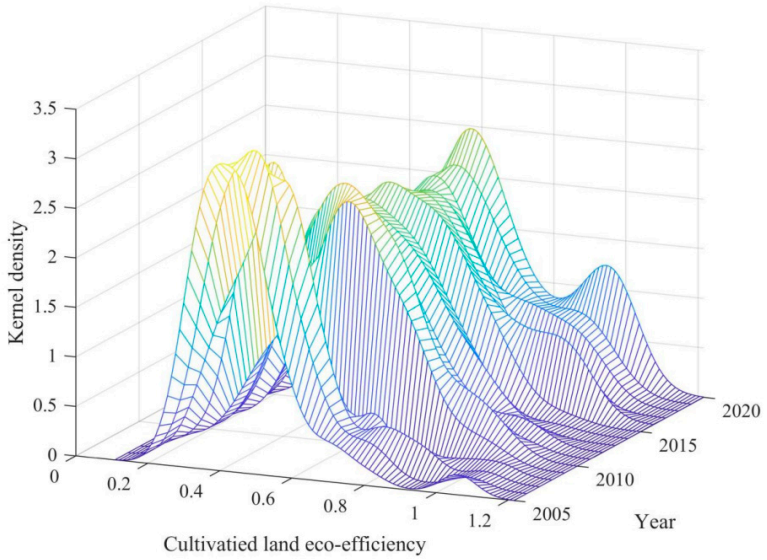

Figure 8. Estimation of kernel density of the ECLU.

4.3. Spatial Evolution Characterization

4.3.1. Traditional Markov Chain Analysis

Markov chain model will be used for analysis in this paper for the sake of disclosing the spatial pattern of the ECLU in the region around Beijing-Tianjin. In the light of the quantile method, the ECLU values are divided into four states: low efficiency, medium-low efficiency, medium-high efficiency, and high efficiency, and expressed as I, II, III, and IV.

As shown in Table 3, the diagonal and non-diagonal values depute the possibility that the ECLU has not shifted and has shifted, respectively. For this, the characteristics reflected are: ① On the diagonal line, the maximum and minimum values are 0.795, 0.610 respectively, which means that there is at least 61% possibility that the ECLU in each county does not shift. However, on the non-diagonal line, the maximum value is much lesser, the maximum value is 0.254, so the probability of shifting between different types is smaller. ②The possibility of remaining unchanged of the ECLU along the diagonal are $P_{IV\text{-}IV}$ (0.795) > $P_{I\text{-}I}$ (0.715) > $P_{III\text{-}III}$ (0.635) > $P_{II\text{-}II}$ (0.610), and the possibility of the first and last of the diagonal are obviously larger, implying that the ECLU have "high-high concentration and low-low concentration". ③The possibility of adjacent diagonal is greater than others, such as $P_{I\text{-}II}$ (0.250) > $P_{I\text{-}III}$ (0.025) > $P_{I\text{-}IV}$ (0.011), implying that the transfer of the ECLU occurs mainly between adjacent types. As a result, it is hard to reach a leapfrog shift. ④ Among the possibility on the adjacent sides of the diagonal, the possibility on the right is higher than that on the left, such as $P_{I\text{-}III}$ (0.238) > $P_{I\text{-}I}$ (0.094), indicating that when the transfer occurs, it is easier to transfer to the direction of high efficiency.

Table 2. Traditional Markov chain probability transfer matrix of the ECLU in the region around Beijing and Tianjin from 2005 to 2020.

Local Status	Ⅰ	Ⅱ	Ⅲ	Ⅳ
Ⅰ	0.715	0.250	0.025	0.011
Ⅱ	0.094	0.610	0.238	0.058
Ⅲ	0.023	0.088	0.635	0.254
Ⅳ	0.000	0.033	0.172	0.795

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4.3.2. Spatial Markov Chain Analysis

The spatial distribution of interrelated geographical objects or attributes is determined on the basis of the first law of geography. Therefore, for the sake of exploring the changes of the ECLU under di-verse environments, introduces the spatial lag and by constructing a spatial Markov transfer matrix, further reflects the influence of neighboring environments on the high or low eco-efficiency of its own arable land use in this paper. In the light of the quantile division method, divide the spatial lag types of the research region into four types: low, medium low, medium high, and high, which were respectively noted as I, II, III, and IV.

According to Tables 3 and 4, the characteristics reflected are: ① Geospatial pattern influences the shift possibility of the ECLU. For example, without considering the geospatial pattern, the possibility of switching from III to II is $P_{III-II} = 0.088$, while when a county borders on a county of type I, $P_{III-II(I)} = 0.259$. ② In general, the transfer of the same type of efficiency occurs, and if a county borders on a county with lower eco-efficiency, the possibility of its shift to the direction of lower efficiency increases, for example, $P_{II-I(I)} = 0.200 > P_{II-I} = 0.094$. Conversely, if it borders on a county with higher eco-efficiency, the possibility of shifting in the direction of high efficiency increases, for example, $P_{II-III(IV)} = 0.294 > P_{II-III} = 0.238$. Taking Caofeidian District of Tangshan City and Gu'an County of Langfang City as an example, the mean of efficiency in the counties around Caofeidian District from 2005 to 2020 is 0.54, which to some extent influenced the ECLU in Caofeidian District from 1.04 to 0.77. The mean value in the counties around Gu'an was 0.55, while the value of the ECLU in Gu'an County increased from 0.35 to 0.44.

The above characteristics show that the geospatial pattern impacts the ECLU in the region around Beijing and Tianjin greatly. The counties with higher eco-efficiency can promote the upward transfer probability of the ECLU in the surrounding counties, which has a positive spillover effect, while the counties with lower eco-efficiency promote the downward transfer of the ECLU in the surrounding counties, which has a passive spillover effect. In the context of geospatial pattern, the ECLU gradually forms a "club convergence" phenomenon of "high clustering and low clustering".

Table 3. Spatial Markov chain probability transfer matrix of the ECLU in the region around Beijing and Tianjin, 2005-2020.

Spatial lag	Local Status	I	II	III	IV
I	I	0.741	0.235	0.012	0.012
	II	0.200	0.543	0.214	0.043
	III	0.037	0.259	0.444	0.259
	IV	0.000	0.130	0.174	0.696
II	I	0.802	0.173	0.025	0.000
	II	0.060	0.655	0.262	0.024
	III	0.000	0.067	0.700	0.233
	IV	0.000	0.026	0.179	0.795
III	I	0.459	0.432	0.081	0.027
	II	0.066	0.632	0.226	0.075
	III	0.015	0.076	0.664	0.244
	IV	0.000	0.016	0.163	0.822
IV	I	0.250	0.750	0.000	0.000
	II	0.000	0.529	0.294	0.176
	III	0.071	0.048	0.571	0.310
	IV	0.000	0.038	0.189	0.774

5. Discussion

5.1. Understanding of Results of the ECLU

In this paper, the ECLU in 71 counties in the region around Beijing and Tianjin was measured by using the Super-EBM model. In terms of research methodology, radial BCC model, non-radial SBM model and EBM model are compared and analyzed, and the results found that radial BCC model > EBM model > SBM model > SBM-Undesirable model, which is because the radial model does not take into account the effect of slack variables, resulting in high results, the non-radial SBM model of the target value of inputs and outputs and the real value of the proportion of the problem of distortion, resulting in low results, and the EBM model circumvents the defects of the two, and the value is in the middle of the two, and is more suitable for the real situation, and the results are in line with the research of Yu et al. [32].

During the research time, the ECLU presented a rising trend, which was consistent with the findings of Zhou et al. [33]. As the growth of urbanization in China, the proportion of GDP in the primary industry gradually decreases, which implies that China's agricultural society is gradually modernizing. During this process, there were significant changes in input factors and agricultural production in the region around Beijing and Tianjin, etc., and coupled with the effect by agricultural policies, the ECLU improved by 87.37% during the research time. However, the ECLU was 0.55, while the result of the ECLU of Hebei Province measured by Liao was 0.9 [34], with a difference of 0.45. This is in addition to the fact that the other municipalities in Hebei Province drove the whole ECLU, Liao used the equivalent factor method to calculate the value of ecosystem services, and placed this indicator into the desired output, which is a positive indicator, but the results obtained from this method were ecosystem service value much higher than others, which finally led to a large difference in the results [35].

As far as the spatial variability are concerned, due to differences in resource endowments, it is characterized by low productivity of arable land, poor arable land in the Taihang Mountains at high altitudes, and poor agricultural supporting equipment in Zhangjiakou and the western mountainous areas of Baoding, thus differences in their innate factors constrain productivity of arable land. However, with the plains areas immediately adjacent to Tianjin, Xiong'an New Area, coastal cities and other ECLU is higher, this is due to the city has a significant radiation effect on the surrounding counties, and therefore will lead to the rapid development of its transportation industry, and the introduction of advanced production concepts and planting technology, which greatly improves the efficiency of the crops from production to sale. Yang took the Yangtze River Basin as the study area and divided it into upstream, midstream and downstream, with the upstream being the Yunnan, Guizhou, Sichuan and Chongqing regions, which have high altitude and poor farming conditions, thus their ECLU is lower, while the downstream includes five cities including Jiangsu, Zhejiang and Shanghai, which have a flat terrain, developed economy, and convenient transportation, which is more conducive to ECLU [21]. The results of both studies agree that there is spatial variability in the ECLU, and that terrain influences the development of ECLU.

5.2. Implications of Characteristics of the Temporal Evolution of the ECLU

Analysis of the time evolution using kernel density estimation shows that ECLU shows a "fast-slow-fast" growth trend. The main reason is that the reduction and exemption of agricultural taxes in 2004 further mobilized farmers' enthusiasm, which led to the rapid growth of the ECLU. From 2010 to 2015, the problem of environmental pollution in agriculture was severe and the awareness of environmental protection was weak, which led to the slow growth of the ECLU. From 2015-2020, China paid more attention to sustainable agricultural development and promoted a virtuous cycle of ecosystems around key construction tasks, thus stimulating the rapid development of the ECLU.

From 2005 to 2020, there has been a "double-peak" phenomenon, indicating that the ECLU has been polarized and has become more pronounced over time, and that differences in agricultural resource endowment, technical level and management level between regions have increased the gap between regions. Moreover, in order to meet the growing demand for food in these less endowed

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regions, the intensity of cropland use has been increasing, and agricultural chemicals have been overused, leading to a further widening of the gap in ECLU. However, due to the "butterfly effect", the technological level and management awareness of the better endowed counties are more advanced, leading to an increase in the ECLU through the adoption of advanced cropland use patterns and moderately controlled intensity of agricultural inputs, which inevitably leads to the polarization of the ECLU as time goes by.

5.3. Insights into Characteristics of the Spatial Evolution of the ECLU

This paper analyzes the spatial Markov chain model and finds that the ECLU in the region around Beijing-Tianjin has the phenomenon of "high and high aggregation, low and low aggregation" in space. It indicates that this polarization phenomenon is also affected by the geospatial pattern, and that the ECLU in the region around Beijing-Tianjin has a significant spatial spillover effect. For example, the higher ECLU in neighboring areas will increase the probability of local ECLU growth, and vice versa. This result demonstrates the spatial correlation and spatial interaction pattern of the ECLU. The results are consistent with those of Chi M and Liu Y [36,37]. Regional development patterns tend to influence land use patterns. Neighboring regions will have similar development patterns, and similar development patterns between regions show similar land resource demand and use patterns [38]. The ECLU in different counties is not spatially independent of each other and is often influenced by the region in which they are located, indicating strong spatial aggregation and spatial interaction effects. In addition, on the basis of the theory of planned behavior, as the speedy growth of the information age, the cultivated land use by farmers depends not only on the farmers themselves [39], but also on the consistency of behavior due to geographical similarity, so the farmers' subjects are also influenced by the behavior of neighboring farmers, and learn and imitate the planting experience of neighboring farmers in order to adjust their own planting methods and maximize their benefits. At the same time, environmental protection strategies and intra-regional economic development patterns are gradually converging as factor flows and interconnecting infrastructure construction within the region tend to improve [40]. The ECLU is affected by the geospatial pattern, and the spatial spillover effect is significant. In this context, the region around Beijing-Tianjin is facing the arduous task of avoiding the low and low agglomeration, and the overall agricultural development is led by the high ECLU region.

6. Conclusions and Suggestions

6.1. Conclusions

In this paper, on the basis of the relevant data from 2005-2020 in the counties in the region around Beijing and Tianjin, we measured the ECLU using Super-EBM, portrayed its temporal evolution characteristics using the kernel density estimation method, also studied its spatial evolution characteristics using the spatial Markov chain model. The core conclusions are as bellow.

(1) By comparing the four models, namely, radial BCC model, SBM model, SBM-Undesirable model and EBM model, the results showed that EBM model was more suitable for the actual situation, so this model was chosen to measure the ECLU. The results show that, in the research time, the ECLU appeared an increasing state, from 0.388 to 0.727, but the average value was only 0.55. Due to the superior transportation location, Chengde, Cangzhou and Tangshan had the highest eco-efficiency, with 0.609, 0.603 and 0.571 respectively, followed by Langfang City, the ECLU value is 0.545, affected by natural conditions, Baoding City and Zhangjiakou City have low eco-efficiency, only 0.517, 0.476 respectively. None of the counties has reached the valid status, and only 9 counties have achieved 0.7 or more. The spatial-temporal pattern of the ECLU shows that the number of inefficient zones is gradually decreasing, and the number of medium efficiency zones, higher efficiency zones and high efficiency zones is increasing. Spatially, there are significant differences between regions, with counties around Tianjin having higher eco-efficiency, and counties in the Taihang Mountain Range, mainly in Zhangjiakou City and the western part of Baoding City having lower eco-efficiency.

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(2) From the time evolution characteristics, the ECLU in the region around Beijing and Tianjin shows an overall "fast-slow-fast" growth trend on account of the kernel density estimation graph. The internal gap in the ECLU widened but stabilized in the research time. The left trailing end of the curve keeps shortening, while the right trailing end first shortens and then increases, and the number of counties with high eco-efficiency increases.

(3) From the spatial evolution characteristics, the probability of not shifting the ECLU in each county is much greater than the probability of shifting, and if shifting occurs mainly between adjacent types, it is hard to reach leapfrogging, and the possibility of shifting to high-value area is greater, but the risk of shifting to the low-value area should be avoided. The geospatial pattern has an essential factor on the efficiency of the county, and it gradually forms a "club convergence" phenomenon of "high-high concentration and low-low concentration".

6.2. Suggestions

In response to the unbalanced development of the ECLU in the region around Beijing and Tianjin, local governments should develop differentiated paths to increase the eco-efficiency according to the resource endowments of different regions.

For areas with high eco-efficiency, such as Cangzhou City, Tangshan City and Chengde City, they should make the best of their location and transportation superiority to further introduce advanced production technologies to enhance the local ECLU while driving the transition of agricultural production methods in the region around Beijing and Tianjin to reach the increase of overall ECLU. Actively cultivate new agricultural business entities while vigorously developing rural secondary and tertiary industries to absorb the remaining agricultural workers.

For areas with medium eco-efficiency, such as Langfang, the city should fully take advantage of its location and topographic advantages of being close to Beijing and Tianjin, make full use of the linkage mechanism of Beijing and Tianjin, further improve the level of local agricultural scale and mechanization, form an agricultural radiation model with Langfang as the core, achieve the integration of agricultural production and marketing, and finally realize the maximum benefit.

For areas with lower eco-efficiency, mainly the mountainous areas in Zhangjiakou and the western part of Baoding, agricultural development plans should be formulated based on their own situation. Specifically, first, the government should meet the needs of local agricultural infrastructure. Secondly, local governments ought to enhance the quality of peasants, encourage them to use arable land efficiently with material rewards, and recommend the use of advanced agricultural production technologies. Third, actively developing three-dimensional mountainous agriculture, developing local economy in multiple aspects, optimizing rural industrial structure, and achieving high-quality agricultural development.

In the light of the fact that the ECLU is caused by the geospatial pattern, it is suggested that the transfer risk of regional eco-efficiency should be comprehensively evaluated, and for high-high agglomeration areas of the ECLU should continue to make use of their agglomeration and should further play its role of demonstration and leadership to move toward higher goals of green cultivated land use. For low level agglomeration areas, establish an early warning mechanism to prevent transfer to low level efficiency regions. Besides, it is essential to found a cultivated land use evaluation institution to provide guidance on resource investment in the procedure of cultivated land use, for the sake of optimizing resource allocation and ensuring the harmonious development of cultivated land economy and ecology.

Besides, the paper has the following two limitations:

(1) When constructing the index system in this paper, there is no absolute standard and unified measurement framework for existing research due to the complexity of arable land use and the limited availability of data. For example, unreasonable use of chemical fertilizers, pesticides and films, in addition to causing carbon emissions, will also produce surface source pollution, while the distribution of surface source pollution is somewhat random, and the current correlation coefficients are difficult to quantify accurately. At this stage, most of the expected outputs only quantify the economic-social outputs, while the procedure of cultivated land use, apart from the negative impact

on the environment, will also produce ecological benefits that are beneficial to human beings. However, the accurate quantification of ecological benefits could be improved. Therefore, the subsequent study should reasonably quantify the source pollution and ecological benefits and include them in the index system.

(2) This paper takes counties (cities and districts) as the research scale to research the ECLU in 71 counties in the region around Beijing and Tianjin. In the future, it can be explored at the microscopic scale. In fact, based on the scale of the plot, it is possible to accurately understand the resource allocation of farmers in the process of cultivated land use, determine efficiency values more accurately, and provide more targeted recommendations. It will provide significant reference for sustainable development as well as ecological civilization construction in the future.

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