Spatial Change of the Farming–Pastoral Ecotone in Northern China from 1985 to 2021

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Abstract: Identifying the spatial changes in farming–pastoral ecotone (FPE) is of utmost importance for the development of strategies for ecological protection in ecologically fragile areas. This study employed spatial autocorrelation and spatial clustering techniques to map FPE at the pixel scale using CLCD data with a spatial resolution of 30 × 30 m in the years 1985, 2000, and 2021, and then analyzed the changes of the FPE in northern China. The results showed that the FPE is mainly located at the border between the Inner Mongolia Autonomous Region and the adjacent provinces, which is along the Hu-line and the 400-mm isohyetal line. The area of the FPE was 63.94 × 10^4 km^2, 62.90 × 10^4 km^2, and 53.81 × 10^4 km^2 in 1985, 2000, and 2021, respectively, accounting for 6.7%, 6.6%, 5.6% of the total land area in China. The FPE boundary moved northwestward during 1985–2021, demonstrating retreating, fragmenting, and shrinking tendencies. The decreased areas and the moving distances of the gravity center are six times and four times greater during 2000–2021 than that during 1985–2000, respectively. Moreover, the discontinuous change in FPE was mainly due to the increase in forest land, especially for the conversion of grassland to forest land. Our findings provide guidance for the construction of ecological civilization and the optimization of ecosystem structure in the farming–pastoral ecotone.

Keywords: the farming–pastoral ecotone; spatial autocorrelation; land use change; de-farming; reafforestation

1. Introduction

Ecotones, referring to transitional areas between different types of landscape [1,2], are especially susceptible to environmental changes [3,4]. The farming–pastoral ecotone (FPE) is located at the arid and semi-arid regions in North China [5]. Increasing studies focus on the spatial pattern of the change in ecotones at the regional and local scales, such as the farming–pastoral ecotone (FPE) [6,7], forest–steppe ecotone [8–10], forest–agriculture ecotone [11,12], and shrub–grassland ecotone [13,14]. Among these studies, the research on farming–pastoral ecotone mainly exists in China, which is a transition zone between agriculture and pastoralism. This FPE is an essential ecological barrier to suppress the southward invasion of deserts [15], while it is also vulnerable to climate change and human activities [16,17]. As a result of climate change, urban expansion, and population increase, ecological and environmental problems have emerged in the FPE, such as severe grassland degradation, ecological environment deterioration, and frequent natural disasters [18]. The Chinese government, therefore, has been carrying out a series of environmental restoration projects, such as the Grain for Green Project. Hence, understanding the dynamic changes in FPE is essential for ecological protection in this ecologically fragile area.

In 1953, Zhao Songqiao proposed the “farming and pastoral transition zone”, a significant transition zone for agriculture and pastoralism, with annual precipitation of approximately 400 mm in the northern Chahar Province, Chahar League, and Xilingol League.
It extends from the Great Wall to the intensive agricultural zone, followed by the extensive agricultural zone, the fixed pastoral zone, the fixed nomadic transition zone, and the nomadic zone [19]. Subsequently, many scholars defined the farming–pastoral ecotone from different perspectives, which can be classified into four major categories, including the definition of FPE based on field investigation data [19], climatic indicators [7,18], comprehensive indicators [20] and land use data [6,21]. There are noticeable differences in the location and area of the FPE among these studies. Furthermore, most studies are based on the administrative units, lacking a definition of the FPE at the pixel scale.

The extent and spatial distribution of the FPE are influenced by climate change (temperature, precipitation, wind speed), social and economic development, politics, military [7,22]. The political and military variations at historical times have resulted in alternating shifts of pushing to the north and pulling back to the southeast [23]. In recent decades, under the influence of climate change and human activities such as population increase and defarming policy [24], many studies showed that the boundaries and distribution of the FPE in China have changed significantly [25]. The change range of the northeast and northern parts is significantly greater than that of the northwest [7]. There is a mutual transformation between cropland and grassland in and around the FPE [26]. The transformation rate between cropland and grassland is the most dramatic among the land types, reflecting the change in FPE [27]. In local areas, land use pattern change was driven by the conversion of forest to grassland in the pastoral-dominated area of Chifeng from 1980 to 2018; in contrast, human activity-oriented land tended to be located in environmentally sensitive areas in agriculture-dominated regions [5].

In addition, the Chinese government has implemented a series of ecology protections [28] which have accelerated the shift in land use and indirectly changed the spatial distribution of the FPE. Since 2012, the government has paid more attention to protecting the ecological environment and cropland. Current research on the change in FPE is focused on the period before 2010. Therefore, updating the research period to the present helps to further identify changes in FPE at different stages of regional differences and deepen the understanding of FPE shifts.

This paper aims to analyze the changes in FPE in northern China from 1985 to 2021 at the pixel scale. The details are as follows: (1) using the area-percentage data of cropland and grassland, this paper proposes a new method to map FPE at the pixel scale, using Local Indicators of Spatial Association (LISA); (2) the method is used to map FPE in 1985, 2000, and 2021, which investigates spatial and temporal changes in FPEs over the past 36 years; and (3) from the perspective of land use change, we explore the causes of the changes in FPEs. The new FPE maps produced by satellite remote-sensing may offer a simple technique for quantitatively assessing how agricultural practices and environmental policies affect vulnerable FPE. Thus, the research results could contribute to ecological protection and regional development in the FPE.

2. Data and Methods

2.1. Data and Preprocessing

Land use data from the CLCD data of Yang Jie and Huang Xin’s team at Wuhan University with a spatial resolution of 30 × 30 km were used to map FPEs in China in 1985, 2000, and 2021 [29]. The data are developed on all available Landsat remote-sensing images on GEE. The data contain nine categories: cropland, forest, shrub, grassland, water, snow/ice, barren, impervious, and wetland (https://doi.org/10.5281/zenodo.5816591) (accessed on 10 August 2022). Based on the Fishnet tool, the percentage of each land type in each 1-km grid was calculated and a 1-km distribution of the percentage area of cropland and grassland was then generated. The spatial–temporal patterns of land use change have been widely studied using the area–percentage data model (APDM) [30,31].
2.2. Methods

2.2.1. A Spatial Autocorrelation Method for Mapping FPEs

To map the FPE in northern China, spatial autocorrelation and spatial clustering techniques could be coupled [6,32,33]. A set of spatial features relating to cluster degree was measured by spatial autocorrelation [34]. The study improved the method of spatial autocorrelation analysis to map FPEs [32]. Spatial autocorrelation analysis involves global spatial autocorrelation analysis and LISA. Global spatial autocorrelation is a description of the spatial characteristics of the attribute values over the whole region. Detecting changes in the spatial interdependence of a given area, LISA is often used to discover the clustering effects of landscape elements in a given region, detect boundaries, and find changing hot issues [35]. In this study, LISA was used to obtain the low- and high-density distribution areas of the percentage of cropland area and grassland area, respectively, which was used to map boundaries of the FPE based on the overlay analysis of the two density distribution maps.

This study used GeoDa (https://geodacenter.github.io/ (accessed on 10 August 2022)) for spatial autocorrelation [36]. Spatial autocorrelation coefficients change with scale and grain size. It has been shown that changing grain size has a significant impact on landscape analysis and that spatial autocorrelation decreases as grain size increases. As the grain size increases, geographical autocorrelation decreases [37]. Therefore, this is a methodology limitation. In this study, GeoDa was input as a vector–grid map of the percentage of national cropland and grassland area, with the range of the adjacency matrix set to 4, which means the adjacency matrix of $9 \times 9$ is the region space. Coefficients of LISA within the adjacency matrix were calculated, and then spatial cluster analysis and significance tests were performed on the autocorrelation coefficients to obtain spatial clustering maps of the percentage of cropland and grassland. LISA was calculated for Not Significant (NN), High–High (HH), Low–Low (LL), High–Low (HL), and Low–High (LH); noted as 1, 2, 3, 4, and 5, respectively (Table 1). LISA of cropland and grassland were combined to obtain 25 types. In this paper, based on the characteristics of FPE, the regions with insignificant and significant positive spatial correlations between cropland and grassland were selected. We established the criteria for mapping the FPE (Table 2).

Table 1. Results and significance of LISA.

<table>
<thead>
<tr>
<th>Results</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>NN</td>
<td>The cell value is not significantly correlated with the surrounding cell values. (default level of significance is $p &lt; 0.05$)</td>
</tr>
<tr>
<td>HH</td>
<td>The cell and the surrounding cell values are both high, and they are significantly positively correlated.</td>
</tr>
<tr>
<td>LL</td>
<td>The cell and the surrounding cell values are both low, and they are significantly positively correlated.</td>
</tr>
<tr>
<td>HL</td>
<td>The cell value is high, while the value of the surrounding cells is low, and they are significantly negatively correlated.</td>
</tr>
<tr>
<td>LH</td>
<td>The cell value is low, while the value of the surrounding cells is high, and they are significantly negatively correlated.</td>
</tr>
</tbody>
</table>

Table 2. Criteria of FPE definition.

<table>
<thead>
<tr>
<th>Id</th>
<th>Cropland</th>
<th>Grassland</th>
<th>Whether It Is Classified as FPE</th>
<th>Position in FPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>NN</td>
<td>NN</td>
<td>Yes</td>
<td>North and south boundary (less)</td>
</tr>
<tr>
<td>12</td>
<td>NN</td>
<td>HH</td>
<td>Yes</td>
<td>North boundary</td>
</tr>
<tr>
<td>13</td>
<td>NN</td>
<td>LL</td>
<td>No, mainly other land use types</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>NN</td>
<td>HL</td>
<td>Yes</td>
<td>North and south boundary (less)</td>
</tr>
<tr>
<td>15</td>
<td>NN</td>
<td>LH</td>
<td>No, less cropland and grassland</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Cont.

<table>
<thead>
<tr>
<th>Id</th>
<th>Cropland</th>
<th>Grassland</th>
<th>Whether It Is Classified as FPE</th>
<th>Position in FPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
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<td>south boundary</td>
</tr>
<tr>
<td>22</td>
<td>HH</td>
<td>HH</td>
<td>Yes</td>
<td>interior</td>
</tr>
<tr>
<td>23</td>
<td>HH</td>
<td>LL</td>
<td>No, mainly cropland</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>HH</td>
<td>HL</td>
<td>Yes</td>
<td>interior</td>
</tr>
<tr>
<td>25</td>
<td>HH</td>
<td>LH</td>
<td>No, mainly cropland</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>LL</td>
<td>NN</td>
<td>No, mainly other land use types</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>LL</td>
<td>HH</td>
<td>No, mainly grassland</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>LL</td>
<td>LL</td>
<td>No, less cropland and grassland</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>LL</td>
<td>HL</td>
<td>No, mainly grassland</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>LL</td>
<td>LH</td>
<td>No, mainly other land use types</td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>HL</td>
<td>NN</td>
<td>Yes</td>
<td>North and south boundary (less)</td>
</tr>
<tr>
<td>42</td>
<td>HL</td>
<td>HH</td>
<td>Yes</td>
<td>interior</td>
</tr>
<tr>
<td>43</td>
<td>HL</td>
<td>LL</td>
<td>No, mainly cropland</td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>HL</td>
<td>HL</td>
<td>Yes</td>
<td>Interior (less)</td>
</tr>
<tr>
<td>45</td>
<td>HL</td>
<td>LH</td>
<td>No, mainly cropland</td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>LH</td>
<td>NN</td>
<td>No, mainly other land use types</td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>LH</td>
<td>HH</td>
<td>No, mainly grassland</td>
<td></td>
</tr>
<tr>
<td>53</td>
<td>LH</td>
<td>LL</td>
<td>No, mainly other land use types</td>
<td></td>
</tr>
<tr>
<td>54</td>
<td>LH</td>
<td>HL</td>
<td>No, mainly grassland</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>LH</td>
<td>LH</td>
<td>No, mainly other land use types</td>
<td></td>
</tr>
</tbody>
</table>

Based on a 1-km grid of the area proportion of cropland and grassland, the regional spatial autocorrelation model was used to initially obtain distribution maps of the FPE in 1985, 2000, and 2021. In this distribution map, small discontinuous regional patches distributed in regions such as the Xinjiang Uygur Autonomous Region, were not considered in this study. Finally, the FPE in northern China was mapped.

2.2.2. Comprehensive Land Use Dynamic Degree (CLUDD)

Land use dynamics can reflect the rate of land use change in the study area. In this study, the comprehensive land use dynamic degree (CLUDD) is used to determine the land use dynamics among different regions.

The model equations are as follows: [38]:

\[
D = \frac{\sum_{i=1}^{n} |S'_i - S_i|}{2\sum_{i=1}^{n} S_i} \times \frac{1}{t_2 - t_1} \times 100\% \quad (1)
\]

where \(D\) is the value of the comprehensive land use dynamic degree, \(i\) is the land use classification type, \(n\) is 9 (9 land use types), \(S'_i\) and \(S_i\) are the areas of land use type \(i\) in \(t_1\) and \(t_2\), \(t_1\), and \(t_2\) are different years.

2.2.3. Gravity Center of FPE

The change in the gravity center can be used to represent evolution characteristics of one geographic element in two-dimensional space. Changes in the gravity center of FPE at different times can show the direction of change of FPEs. This paper calculates the gravity center of FPE in 1985, 2000, and 2021 to study the moving direction, distance, and speed of the FPE.

3. Results

3.1. Spatial Distribution of the FPE in Northern China in 1985, 2000, and 2021

The distribution range of the FPE is consistent with the trend of the Hu-line (Heihe–Tengchong line) and roughly runs along the 400-mm isohyetal line (Figure 1). The FPE was mainly distributed in the Inner Mongolia Autonomous Region, Shanxi Province, Gansu Province, Shaanxi Province, Hebei Province, Ningxia Hui Autonomous Region, Liaoning Province, Jilin Province, and Qinghai Province. In 1985, 2000, and 2021, the area of the FPE
was $63.94 \times 10^4 \text{ km}^2$, $62.90 \times 10^4 \text{ km}^2$, and $53.81 \times 10^4 \text{ km}^2$, respectively, accounting for 6.7%, 6.6%, 5.6% of the total land area in China and showing a decreasing trend. Spatially, the FPE showed a continuous distribution in 1985, which was connected into a whole space (Figure 1). In 2000, the FPE showed a trend of fragmentation, especially in the apparent discontinuous area near Chengde city, Hebei Province, where the FPE was divided into two parts. In 2021, the fragmentation of the FPE was more obviously. In the discontinuous area near Yan’an city, Shaanxi Province, the FPE was found in three parts. The fragmentation trend of the FPE likely intensified due to the afforestation conversion of cropland and grassland to forest land.

Figure 1. Maps of the farming–pastoral ecotone (FPE) in Northern China in 1985, 2000, and 2021.

3.2. Change in the FPE in Northern China from 1985 to 2021

The increased area of the FPE from 1985 to 2021 was mainly distributed in the northern part of the FPE (within Inner Mongolia Autonomous Region, Jilin Province, and Liaoning Province), the central part of the Inner Mongolia Autonomous Region and Gansu Province, and Ningxia Hui Autonomous Region. The area was small, with a total of $3.61 \times 10^4 \text{ km}^2$. The decreased area was $13.74 \times 10^4 \text{ km}^2$, mainly distributed in the northern and central parts of the FPE, with the largest decreased area at the boundary between Shaanxi Province and the Inner Mongolia Autonomous Region (Figure 2).
Figure 2. Spatial distribution of increase, decrease, and unchanged regions in FPE from 1985 to 2021.

A fragmentation of FPE in Northern China was shown in 2000 and 2021, mainly located at the junction of Hebei and the Inner Mongolia Autonomous Region (Area 1) and the Shaanxi Province and Inner Mongolia Autonomous Region (Area 2) (Figure 2). Area 1 is located near the city of Chengde, and Area 2 is located near the city of Yan’an. Area 1 and Area 2 were used to separate the FPE into eastern, central, and western parts. The increased area of the FPE in the east was mainly located in the eastern Inner Mongolia Autonomous Region, with increased areas of 7500 km$^2$ and 2500 km$^2$, respectively. The increased space in the central part was primarily located in the Inner Mongolia Autonomous Region and Shaanxi Province, with an increased area of 3300 km$^2$ and 2900 km$^2$, respectively. The increased areas in the western region were mainly located in the Ningxia Hui Autonomous Region and Gansu Province, with areas of $1.68 \times 10^4$ km$^2$ and 2800 km$^2$, respectively. Meanwhile, the FPE located in the Ningxia Hui Autonomous Region was separate from the main FPE in 1985, but it became whole in 2021. The decreased areas of Area 1 and Area 2 were 6233 km$^2$ and $3.69 \times 10^4$ km$^2$, respectively. The reduced area of the FPE in the eastern region was 9200 km$^2$ at the northernmost end and $2.61 \times 10^4$ km$^2$ on both sides. The area that decreased in the center was mainly on both sides, with an area of $5.00 \times 10^4$ km$^2$. There was a smaller area reduced in the western region, mainly located on both sides of the region, with an area of 6300 km$^2$. In summary, the largest decreased area of the FPE was situated in the central part.
The rates of area decrease in FPE was varied with different periods (Figure 3). Compared with 1985, the area of the FPE in 2021 decreased by $10.13 \times 10^4$ km$^2$, with a decrease rate of $0.28 \times 10^4$ km$^2$/a. The area decreased by $1.04 \times 10^4$ km$^2$ at a rate of $0.07 \times 10^4$ km$^2$/a from 1985 to 2000. The area decreased by $9.09 \times 10^4$ km$^2$ at a rate of $0.43 \times 10^4$ km$^2$/a from 2000 to 2021. The reduction rate after 2000 is six times that before 2000. The FPE has the largest area in the Inner Mongolia Autonomous Region, with $25.78 \times 10^4$ km$^2$, and $25.999 \times 10^4$ km$^2$, $23.89 \times 10^4$ km$^2$ in 1985, 2000, and 2021, accounting for 40.32%, 41.33%, and 44.39% respectively. The area firstly increased and then decreased, but the area proportion has been growing, which shows that the distribution area of the FPE is increasing within the Inner Mongolia Autonomous Region. The area of the FPE in other provinces also decreased from 1985 to 2021.

![Figure 3. Area and area proportion of FPE in different provinces. (a) Area; (b) Area percentage.](image)

The gravity center of the FPE in Northern China is in the Shanxi Province and moved northwestward from 1985 to 2021. Specifically, moving southwestward during 1985–2000, and northwestward during 2000–2021 (Figure 4). From 1985 to 2021, it moved northwestward as a whole. Then from 1985 to 2000, the gravity center moved 3.60 km southwestward, with an average annual movement of 0.24 km/a. From 2000 to 2021, the gravity center moved 22.87 km to the northwest, with an average annual movement of 1.09 km/a. The moving distance of the gravity center from 2000 to 2021 is more than six times that from 1985 to 2000, and the moving speed is more than four times. These results indicate that the rate of change in the FPE increased after 2000.

3.3. Land use Change in the FPE Buffer Zone

To discuss the discontinuity of the FPE, a 50-km buffer zone was generated by the FPE boundary in 1985, and the land-type conversion and comprehensive land use dynamic degree were analyzed. The land use changes in two discontinuous areas Area 3 and Area 4 were analyzed (Figure 5).
Figure 4. Gravity center of the FPE in 1985, 2000, and 2021.

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Figure 5. Map of 50-km buffer zone of the FPE in 1985.

3.3.1. Land Use Change within the Whole Buffer Zone

Overall, forest and impervious surfaces increased in the 50-km buffer zone, while the area of other land use types, such as cropland and grassland, decreased (Figure 6). A total of 5.71 × 10⁴ km² grassland was converted into cropland, and 7.73 × 10⁴ km² cropland was converted into grassland.

The increase of forest land in 2021 is mainly from the conversion of grassland in 1985, accounting for 82.42% of the increased area. The cropland area converted into the impervious surface is 13,100 km², accounting for 75.73% of the increased area of impervious surface. The reason for the movement of FPE from 1985 to 2021 is the conversion of cropland and grassland into forest land and impervious surface, mainly to forest land.

The land use change in different regions is different from 1985 to 2021, and it is measured by the spatial distribution of land use dynamic degree of a 1-km fishnet (Figure 7). The northern and central of the FPE in northern China exhibited remarkable land use change, mainly distributed in the Shaanxi Province, and the northern and central Inner Mongolia Autonomous Region. The comprehensive land use dynamic degree in the discontinuous areas of FPE is also obviously (Area 1 and Area 2).

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3.3.2. Land use Change in Area 3 and Area 4 of the Buffer Zone

In 2000, discontinuity began to appear in Area 1 of the FPE, and the land use of Area 3 in the buffer zone was selected for research. The study found that the area of forest land in this region showed an increasing trend from 1985 to 2000, and the forest land was mainly converted from grassland. The area of this type of conversion increase accounted for 81.34% of the total increased area (Figure 8). In 2021, discontinuous areas also appeared in the FPE (Area 2) at the junction of the Shaanxi Province and the Inner Mongolia Autonomous Region. We analyzed the dynamic land use changes in Area 4 from 2000 to 2021. The results showed that the area of forest land and impervious surface increased in this region, while the area of other types decreased. Among them, the area of forest land increased more, mainly transformed from grassland, and the increased area of this type of transformation accounted for 87.16% of the total increased area (Figure 9).
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Figure 7. Map of 1-km fishnet grid of comprehensive land use dynamic degree (CLUDD).

Figure 8. Shifts in land use types in Area 3 from 1985 to 2000.
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![Figure 8. Shifts in land use types in Area 3 from 1985 to 2000.](image)

![Figure 9. Shifts in land use types in Area 4 from 2000 to 2021.](image)

### 4. Discussion

#### 4.1. Comparative Analysis of Methods on the FPE in Northern China

In this study, the area-percentage of cropland and grassland was used as an indicator to identify the spatial distribution of FPE from 1985 to 2021 using LISA and classification criteria based on the diversity of the FPE.

Compared to earlier FPE maps produced using field investigation data [19], climatic indicators [7,18], comprehensive indicators [20], and land use data [6,21], our proposed FPE map was different. The FPE in northern China in 2000 was selected for comparative analysis with other FPE methods (Table 3). The spatial distribution of the FPE obtained in this study approximately parallels the previous results obtained by the climate method and land use proportion method [21] but differs in length, width, and area (Figure 10). At the boundary of the three northeastern provinces in high latitudes, the method based on climate data and land use data has a broader range of applications involving the Heilongjiang Province, while our proposed FPE is mainly distributed in the Inner Mongolia Autonomous Region. In the scope of the FPE near the Shaanxi Province and Inner Mongolia Autonomous Region in the middle latitude, the results of this study have a broader regional distribution width. The spatial distribution trend of other regions except for the ones mentioned above is the same. In general, the overall spatial distribution trend obtained in this study is relatively consistent with earlier FPE. It is consistent with the distribution trend of key regions in the northern FPE announced by the Ministry of Agriculture of China, mainly extending along the direction of the Hu-line (Figure 10), which shows that our method is suitable for dividing the FPE.
Table 3. Comparative Analysis of FPE with Different Criteria.

<table>
<thead>
<tr>
<th>FPE Criteria Area (10^4 km^2)</th>
<th>Criteria</th>
<th>Area (10^4 km^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wenjiao Shi, et al. [21], FPE boundary based on climatic factors in 2000</td>
<td>Based on the defined area with annual precipitation variability of 15–30% and dryness index of 0.2–0.5, the 400-mm isoline of annual precipitation is taken as the center, the 300-mm isoline is taken as the northwest boundary, and the 500-mm isoline is taken as the southeast boundary. Unclosed parts of the northwest and southeast boundaries are smoothly transitioned from 300-mm to 500-mm through 350-mm, 400-mm, and 450-mm precipitation isolines.</td>
<td>68.02</td>
</tr>
<tr>
<td>Wenjiao Shi, et al. [21], FPE in 2000 based on land use data</td>
<td>Within the scope of the existing ecological division of the northern FPE, the contiguous area is extracted. This area must meet the conditions of the proportion of cultivated land &gt;15%, the proportion of grassland &gt;15%, and the proportion of cultivated land and grassland &gt;50% in the land use percentage grid.</td>
<td>66.58</td>
</tr>
<tr>
<td>Key Region Scope of Northern FPE (2016) [39]</td>
<td>County agricultural structure</td>
<td>45.90</td>
</tr>
<tr>
<td>Our results in 2000</td>
<td>Spatial autocorrelation analysis of cropland and grassland</td>
<td>62.90</td>
</tr>
</tbody>
</table>

Figure 10. The spatial distribution of FPE with different criteria. Our FPE in 2000 is our result for the year 2000. Key region is the key area of the northern FPE released by the Ministry of Agriculture of the People’s Republic of China. PRE_Precip2000s is the boundary of the FPE based on climatic factors in 2000. PRE_LUCC2000s is the boundary of the FPE based on land use data in 2000.
In addition, there are also studies using spatial autocorrelation analysis to divide the FPE, but the different classification criteria will lead to differences in the results. This kind of method is also significant in the division space, and the area of the distribution of the FPE covers the Henan Province, Guizhou Province, Yunnan Province, and other regions [7]. The division criteria are formulated from the perspective of the multiattribute principle of the FPE. Our proposed FPE map is more line with the boundary of the FPE in northern China studied by the most scholars [40].

In previous studies, some scholars used the land use method to divide the FPE, which needed to use the proportion data of forest land, grassland, and cropland in the region, and manually digitally draw the FPE [21]. This method consumes many workforce and material resources and is easily affected by the subjective judgment. In this study, the spatial autocorrelation method is introduced, and LISA is used to divide the boundary of the FPE from the perspective of spatial heterogeneity. The main principle is that the cropland and grassland in the FPE have a strong correlation; they have insignificant areas and the characteristics of regions interlaced at the same time. To a certain extent, this method reduces the working time and weakens the influence of subjective judgment on the division of the FPE.

4.2. Changes in the Northern FPE

Under the background of climate change and the intensification of human activities, the FPE has undergone some changes. We found a decreasing trend in the area of the FPE from 1985 to 2000. The results are similar to those of other scholars [6]. However, it is worth noting that results from other scholars for the 2000–2010 period found that the FPE area is increasing [6], which is contrary to the results found in this study. The reason may be that, after 2010, the government introduced a variety of support measures for agriculture and a rural revitalization plan, and the gravity center of cropland moved northward [41], making the area of FPE show a decreasing trend. The decrease in FPE is mainly due to the continued implementation of policies such as returning farmland to grassland and reducing the shelter-forest system. At the same time, the urban land in the FPE increased, showing the coexistence of the policy of returning farmland and the occupation of cropland by urban land [24]. The reduction in the FPE area may affect ecological and environmental changes, such as the reduction of biodiversity, ecosystem instability, and other issues. The biodiversity within the ecotone is high but unstable, and is vulnerable to environmental changes when changes occur, such as species extinction, which affects the stability of the ecosystem.

Before 2000, the gravity center of the FPE moved southwestward, mainly due to grassland degradation and desertification. After 2000, the state implemented environmental protection projects to alleviate grassland degradation, but desertification still exists [42]. Implementing policies such as returning farmland to grassland and returning farmland to forest have led to the overall trend of the FPE moving northwestward in 2000–2021, while domestic studies show that the dry and wet climatic zone in China is moving southeastward in the opposite direction [43]. From the perspective of climate, the direction of the FPE should be biased toward the southeast because the humid and warm environment is more suitable for crops on cropland. However, due to drought in the climatic region [44], the FPE in China is still moving northwestward. The possible reason is that human activities are having more influence on the FPE. Some scholars have found that 60% of all land changes result from direct human activity and 40% from indirect factors such as climate change [45]. Also, cropland is breaking through the climatic boundary and moving northwestward, while the farming boundary is moving northwestward [46].

In this paper, the movement of the FPE to the northwest is mainly due to the direction of cropland and grassland and the conversion of cropland and grassland into forest land. The movement of FPEs has an essential impact on the ecological environment. The increase of forest land can improve wind protection and sand fixation capacity, reduce soil erosion, and prevent soil desertification, but it will also accelerate the consumption of groundwater.
resources in arid and semi-arid areas [42], which may increase the risk of water shortage. This is not conducive to agricultural production activities. Artificial vegetation has already exacerbated some ecological issues, including increased water competition between human society and the ecosystem, and it displays lower net primary production and precipitation use efficiency than natural vegetation [47]. It is worth pondering whether converting grassland into forest land is a suitable ecosystem change according to the laws of nature. Drought-tolerant and stable carbon-sequestration plants (grass and shrub, etc.) would be preferred in ecological restoration over plants that need a large amount of water.

4.3. Fragmentation Trend in FPE

This study found that the FPE appeared to have intermittent regional faults after 2000. Such areas are mainly distributed at the junction of the Hebei Province and Inner Mongolia Autonomous Region, located near Chengde city, Hebei Province. In 2021, regional discontinuity also appeared at the intersection of the Shaanxi Province and the Inner Mongolia Autonomous Region, located near Yan’an city. By analyzing the land use data of this area, it was found that discontinuous Area 1 from 1985 to 2000 and the discontinuous Area 2 from 2000 to 2021 are both the result of grassland conversion into forest land. It shows that afforestation in the FPE is also the main reason for migration and differentiation in the FPE. The afforestation near Chengde started earlier, which belongs to the implementation area of the Beijing–Tianjin sandstorm source-control project, and forest land increased. From 1985 to 2000, the project of returning farmland to forest and grass was not implemented near Yan’an city, and the discontinuous Area 2 did not appear. After 2000, the project of returning farmland to forest and grass was implemented near Yan’an city, and forest land increased [48]. Some studies have shown that the landscape fragmentation index in China is raised, and the fragmented landscape pattern was the combined effect of the physical–geographical environment and human-activity interference. Landscape fragmentation showed relatively prominent fluctuation features in the southwest–northeast Hu Line [49].

The fragmentation trend area decreased in the FPE may result in degradation of the FPE as a barrier to desertification, which will cause an increase in the area of arid land and desertification of the soil [42,44]. The appearance of the discontinuous regions makes the FPE patchy. It causes landscape fragmentation, which can cause a decrease in biodiversity [50], reduce ecological service-value trade-offs and synergies [51], and increase the instability of ecosystems. It will increase the degradation rate of FPE.

4.4. Limitations and Perspective

Although new FPE maps in Northern China have been created using satellite remote-sensing data, and more research has been done to better understand the spatiotemporal variations in FPEs, there are still a number of issues that need to be addressed in future studies. Firstly, the effect of the precision of land use data should be investigated. Different land use data with different resolutions have additional accuracy [52], which has a more significant impact on the results of the study of FPE. Therefore, dynamic changes must be studied with consistent land use data. The division of farming–pastoral ecotone will also be studied for different land use data in future studies. A significant scientific obstacle in studies of landscape ecology is the scale effect. Scale size has an impact on the spatial distribution of results [53]. The grain size of the fishnet, which generates the area percentage of cropland and grassland, also has a significant effect. The FPE boundaries are rougher when the grain size is larger. In this paper, a 1-km grid size for the analysis was chosen. The results are different when a 10-km grid size is selected [6]. Also, different resolutions of land use data used to calculate grid data result in different FPEs [6,32]. Generally, the smaller the grain size is, the more accurate the study results will be, but the workload will also increase. Therefore, in this paper, a 1-km grid size of fishnet was chosen to consider grain size and workload. The FPE is a global phenomenon, however, we find a lack of global-scale FPE research. In a future study, the global FPE will be defined.
5. Conclusions

This study identified the FPE at the pixel scale in northern China by integrating the spatial autocorrelation method with a 1-km grid size of area-percentage of cropland and grassland area obtained from remote sensing-based land use data. We also mapped the spatial distribution of the FPE in 1985, 2000, and 2021. The FPE was mainly distributed in the Inner Mongolia Autonomous Region and the northeastern provinces, Hebei Province, Shanxi Province, Shaanxi Province, and Gansu Province. In 1985, 2000, and 2021, the area of FPE was $63.94 \times 10^4 \text{ km}^2$, $62.90 \times 10^4 \text{ km}^2$, $53.81 \times 10^4 \text{ km}^2$, respectively, accounting for 6.7%, 6.6%, 5.6% of the total land area in China. This indicated that the FPEs showed a decreasing trend in the area and a trend of fragmentation from 1985 to 2021. The gravity center of FPEs showed a trend of moving northward, and the distance moved during 2000–2021 was more than six times the distance moved during 1985–2000, while the speed of movement was more than four times. Moreover, in 2000 and 2021, a discontinuous area of the FPEs appeared, mainly on the border among the Hebei Province, Shaanxi Province, and Inner Mongolia Autonomous Region. By studying the land use change within the 50-km buffer zone of the FPE in 1985, we suggest that the main reason for the trend of fragmentation is the conversion of regional grassland into forest land. We will study the impact scale size of land use on defined FPEs and identify global FPEs in the future.

Author Contributions: Z.L.: conceptualization, methodology, and writing; L.L. and Y.W.: writing—review and editing; W.M.: paper revision; W.L. and Q.N.: supervision. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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