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The Spatial Distribution of Fallow Land and Its Ecological Effects in the Agro-Pastoral Ecotone of Northern China

Haoran Cao and Mei Meng *

College of Public Administration, Xinjiang Agricultural University, Urumqi 830052, China; 18734074180@163.com
* Correspondence: mengmeihh@163.com

Abstract: Fallowing is a widely adopted approach for land restoration and ecological protection in the agro-pastoral ecotone of northern China. However, research on the ecological impacts of fallowing in this ecologically fragile region is still limited. With the implementation of fallow policies, it is essential to update the delineation of fallow areas to reflect current practices and ecological considerations. This study developed an index system to assess ecological vulnerability and subsequently delineated fallow areas based on urgency. The ecological effect of fallowing was evaluated using the Ecological Index. Our results show that priority and secondary priority fallow areas are predominantly located in the northern and central regions of the northern agro-pastoral ecotone, covering approximately 33.46 $\times$ 10^4 km^2 by 2023. During the implementation of the fallow policy from 2015 to 2019, the Ecological Index of each county increased, indicating improved environmental quality. However, from 2019 to 2023, the ecological status declined in all three counties, with minor changes in Guyuan County and Fengzhen City. Notably, the ecological degradation rate was faster in Huan County without the second round of fallow. These results indicate that fallowing has a beneficial effect on various aspects of the ecological environment in arid and semi-arid regions, including soil and water conservation, water network density, and vegetation coverage. Furthermore, this improvement demonstrates a sustained effect over time.

Keywords: fallow ecological; effect of fallow; spatial layout; the agro-pastoral ecotone of northern China

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1. Introduction

Cultivated land serves as the fundamental resource foundation and spatial foundation necessary for human survival and the advancement of agricultural civilization. The ongoing protection of the ecological security of cultivated land is a critical step toward ensuring food security and fostering the development of ecological civilization. However, the excessive exploitation and utilization of cultivated land by humans has increasingly emerged as significant threats to global food security and ecosystem stability [1]. In the 21st century, the United States and China, as the leading global producers of grain, have managed to sustain growth in grain production despite a reduction in domestic arable land [2]. This achievement can be attributed to the intensive utilization of cultivated land resources, along with the widespread application of chemical fertilizers and pesticides [3]. Nonetheless, these practices have resulted in the degradation of sustainably managed agricultural land and an escalation in soil erosion, desertification, and land salinization. Survey results indicate that in the United States, approximately 80 $\times$ 10^4 km^2 of cultivated land is affected by a single form of degradation, accounting for more than 60% of the country's total cultivated land area. In China, around 60 $\times$ 10^4 km^2, or 58%, faces similar challenges, while

about 60% to 70% of cultivated land in the European Union is experiencing one or more forms of degradation [4].

In response to these challenges, numerous countries and regions have implemented fallow policies aimed at enhancing soil fertility. Fallowing serves as a crucial strategy for protecting cultivated land and restoring ecological integrity. It is a widely adopted agricultural practice in developed nations, designed to improve soil fertility, increase yields, and safeguard ecological health [5]. Since 1986, the United States has enacted an environmentally sustainable fallow program, wherein the United States Department of Agriculture has established varying maximum compensation amounts for different types of cultivated land across regions based on relative productivity and land rental prices nationwide [6]. This initiative has been instrumental in preventing soil erosion, enhancing agricultural productivity, and conserving natural resources in the U.S. Similarly, the European Union launched the MacSharry set-aside reform in 1992 to enhance soil fertility and mitigate the environmental impacts of agricultural practices. However, the set-aside ratio is dynamic; arable land retention is continuously adjusted in response to prevailing food security conditions [7]. In June 2016, the Ministry of Agriculture and Rural Affairs of the People's Republic of China issued a Pilot Program to Explore the Implementation of Farmland Rotation and Fallow System. This proposal explicitly outlined pilot set-aside programs across five provinces, encompassing various ecological zones, including groundwater funnel areas in Hebei, heavy metal-contaminated regions in Hunan, karst desertification areas in the Southwest, and severely ecologically degraded regions in the Northwest. The initiative is grounded in two fundamental prerequisites: the safeguarding of national food security and the preservation of agricultural household income levels [8]. China aims to enhance its ecological protection and restoration policies while also fostering an inter-regional linkage development mechanism. Achieving these objectives necessitates two critical actions: first, the scientific identification of fallow areas, and second, the evaluation of the ecological effects of policy implementation. These steps will facilitate more effective policy formulation and execution in the future.

Following the implementation of China's cropland fallow policy in 2016, multidisciplinary research has focused on several critical issues, including the extent to which the anticipated fallow objectives have been achieved, the effectiveness of national ecological security safeguards, and the maximization of ecological effects alongside soil fertility enhancement. These interconnected questions have constituted the primary concerns and focal points of scholarly investigation and theoretical discourse within the context of China's agricultural and environmental policy evaluation. Research on the ecological impacts of policy implementation has primarily concentrated on three key areas: the effects of the policy on soil erosion, biodiversity, and hydrological conditions. Scholars have extensively examined these dimensions to assess the ecological outcomes of the implemented measures. A research team from the University of Kent developed various strategies to optimize fallow land in Borneo's oil palm plantations, aiming to maximize both crop production and ecological benefits, including biodiversity, nutrient cycling, and above-ground carbon sequestration [9]. Their research revealed a significant finding regarding ecological efficiency, identifying the most effective land-use configuration as comprising 85% cultivated land and 15% diversified fallow land, which demonstrated the highest ecological effectiveness among the tested scenarios. Numerous international studies have investigated the impact of green manure cultivation during fallow periods on soil fauna. Notably, the researchers conducted a comparative study under conditions devoid of chemical fertilizers, focusing on two distinct scenarios: fallow plots with leguminous plant cultivation and control plots left idle. Their findings indicated a significant difference in soil macrofauna, with plots planted with legumes exhibiting higher abundance and biomass compared to

uncultivated control plots [10]. Additionally, in the practices of fallow land management, the application of kudzu as green manure significantly increased the density of soil mites and earthworms relative to natural fallowing. The green manure covers played multiple ecological roles, mitigating soil erosion caused by rainfall and thereby preserving the habitat for soil fauna while enriching the nutritional resources available to soil organisms. These combined effects resulted in a heightened density of soil fauna, creating a more favorable environment for the proliferation of soil-dwelling organisms [11]. Regarding hydrological conditions, agricultural water consumption could be effectively reduced by altering crop types, improving agricultural practices, and strategically planning fallow periods [12]. Other researchers had modeled hydrological cycles in rotational farmlands under a complete fallow scenario at a regional scale, assessing the contribution of fallowing to shallow groundwater resource recovery. Findings revealed that the implementation of fallow policies positively impacted shallow groundwater restoration, demonstrating that fallowing did not result in soil "wetting" risks in the surface layer of fallow land [13]. This comprehensive approach provided valuable insights into the hydrological implications of fallow policies without compromising soil-water environmental conditions. The effects of fallow policy implementation on soil physicochemical properties have emerged as a significant focus of scholarly research. For instance, fallowing can enhance soil organic matter, total nitrogen, available phosphorus, and available potassium, thereby increasing crop yields and reducing chemical fertilizer usage, ultimately achieving cost savings and enhanced efficiency [14]. Furthermore, some scholars observed a positive correlation between effective nitrogen storage in plants and the duration of fallow when examining the relationship between upland rice yield, fallow length, and soil properties [15]. Concurrently, organic carbon and total nitrogen content, as well as pH levels in the surface soil (0–10 cm), were significantly lower compared to land under intensive management practices [16].

China is confronted with significant challenges relevant to land degradation, particularly evident in the agro-pastoral ecotone of northern China, which is situated in arid and semi-arid regions [17]. This area is marked by severe land degradation, primarily manifested through desertification, soil salinization, and erosion. These environmental challenges can be predominantly attributed to a confluence of factors, including an arid climate, scarce and unevenly distributed precipitation, overgrazing, and unsustainable agricultural practices [18]. Despite the Chinese government's initiation of ecological restoration projects in 2000, such as the Grain for Green Program and the Beijing-Tianjin Sandstorm Source Control Project [19], the cultivated lands within the agro-pastoral ecotone of northern China continue to exhibit high vulnerability. This persistent susceptibility is the consequence of a complex interplay of multiple factors, underscoring the ongoing challenges associated with achieving sustainable land management in this ecologically sensitive region. The fundamental objectives of this study are: (1) to identify the fallow area layout within the agro-pastoral ecotone based on the vulnerability of cultivated land; (2) to evaluate the ecological impacts of typical fallow counties before and after the implementation of relevant policies.

2. Materials and Methods

2.1. Study Area

This study utilizes the 2016 Guidance on Agricultural Structure Adjustment in the agro-pastoral ecotone of northern China, issued by the Ministry of Agriculture and Rural Affairs, as a benchmark for delineating the research area. This area (34°35′–45°30′ N, 102°55′–123°28′ E) encompasses 145 counties (including cities, banners, and districts) across seven provinces, covering a total area of approximately 461,700 km^2. The agro-pastoral ecotone of northern China is located in the transition zone between semi-humid and semi-arid regions of the country. The northern agro-pastoral ecotone is located in the transitional development area between the

traditional agricultural and pastoral regions of northern China. This zone experiences land use confusion due to ambiguous land planning, and it is characterized by ecological vulnerability. The average annual precipitation in this area ranges from 300 to 450 mm, exhibiting notable inter-annual fluctuations between dry and wet periods, alongside substantial evaporation rates. This region, positioned at the junction of the second and third topographical steps, is characterized by complex and diverse landforms, predominantly comprising plateaus and mountains.

Prolonged intensive land reclamation and overgrazing have exacerbated land desertification in the area, with an inter-annual growth rate of desertification in the semi-arid portion of the agro-pastoral ecotone east of Helan Mountain recorded at 1.39% [20]. Concurrently, ongoing land reclamation efforts have significantly increased regional agricultural water usage, resulting in pressing issues such as river discontinuity and groundwater depletion. Since 2000, the Chinese government has implemented farmland protection strategies aimed at restoring degraded lands within the northern farming-pastoral ecotone. These strategies specifically target desertification and degradation zones along the Great Wall, the Beijing–Tianjin–Hebei water conservation areas, and the loess hilly and gully regions (Figure 1).

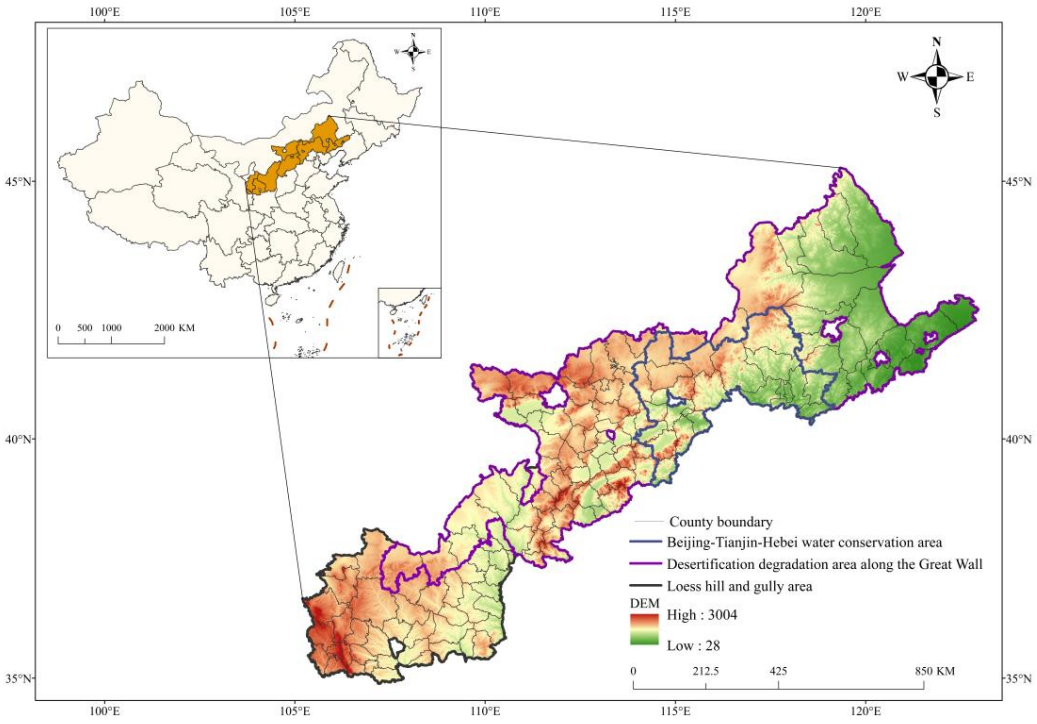

Figure 1. Research area.

2.2. Data Sources and Pre-Processing

The social and economic data utilized in this research were sourced from the 2015–2023 China Rural Statistical Yearbook, China Counties Database, and statistical yearbooks from various cities and counties. In instances where null values were present in specific areas, these gaps were addressed by calculating mean growth rates based on the original data. The NDVI (Normalized Difference Vegetation Index) data were derived from the monthly 1 km MOD13A3 dataset released by NASA, with the NDVI values for the period 2015–2023 processed using the maximum synthesis method. The NDVI data utilized in this study were sourced from NASA's MOD13A3 dataset. Specifically, the NDVI band within the dataset was selected for direct maximum synthesis, and the average NDVI value for each of the 12 months of the year was calculated to obtain the annual NDVI value. Rainfall data were derived from the Tibetan Plateau data platform in China, and Kriging interpolation has

been verified for precipitation stations. Meteorological data were primarily obtained from the China Meteorological Data Network (https://data.cma.cn, accessed on 26 August 2024), while land use data were sourced from the 30 m × 30 m annual land cover dataset (CLCD) provided by Wuhan University. The digital elevation model (DEM) was derived from NASA's product datasets, and soil data were obtained from the HWSD 2.0 (Harmonized World Soil Database).

2.3. Research Framework and Study Methods

2.3.1. Research Framework

High-quality arable land is essential for achieving optimal grain yields within a region. Such land typically exhibits robust soil fertility and efficient agricultural infrastructure, resulting in high productivity. It serves as a fundamental cornerstone for regional food security; however, the marginal benefits derived from soil fertility improvements post-fallow are relatively minimal, indicating that not all cultivated lands are ideal candidates for fallowing [21]. In arid and semi-arid regions, a combination of environmental factors and unsustainable agricultural practices has led to degraded soil fertility and insufficient infrastructure in part of cultivated land. The use of green manure and the improvement of saline-alkali lands can effectively enhance soil fertility while simultaneously mitigating non-point source pollution from agricultural activities. Accordingly, from the perspective of "ecological maintenance, ecological resilience, and ecological pressure", it is imperative to prioritize fallow in areas of cultivated land characterized by severe ecological fragility.

Fallow directly caused changes in land cover and biological abundance, which subsequently altered traditional agricultural landscape patterns, thereby impacting the regional ecosystem [22]. Therefore, it is imperative to analyze land use patterns following fallow implementation, identify shifts in land utilization, and evaluate the maintenance of dynamic equilibrium in cultivated land areas after achieving fallow objectives [23]. Water resources are a critical factor limiting development in arid regions [24]. Planting green manure crops on fallow plots can effectively reduce soil moisture evaporation, thereby influencing river runoff and river network density. Therefore, hydrological factors have been incorporated into the ecological environment assessment system. Vegetation plays a critical role in regulating energy exchange and carbon cycling within terrestrial ecosystems, with changes in vegetation serving as vital indicators of ecological conditions and human activities [25]. Fallow tillage actively promotes vegetation restoration and protection within the region [26], enhancing carbon storage in surface vegetation either directly or indirectly through the continuous succession toward higher [27].

In ecologically fragile farming-pastoral ecotones, fallowing directly improves the ecological environment by optimizing soil texture and increasing soil nutrients. Soil erosion represents a significant challenge that has long hindered the sustainable development of the agro-pastoral ecotone in northern China. This region, characterized by fragile geomorphological soil conditions and arid climatic influences, is particularly susceptible to both water and wind erosion. Therefore, when evaluating the ecological effects of fallowing, changes in the degree of soil erosion can serve as a direct indicator of the extent of ecological recovery in the region following fallow practices (Figure 2).

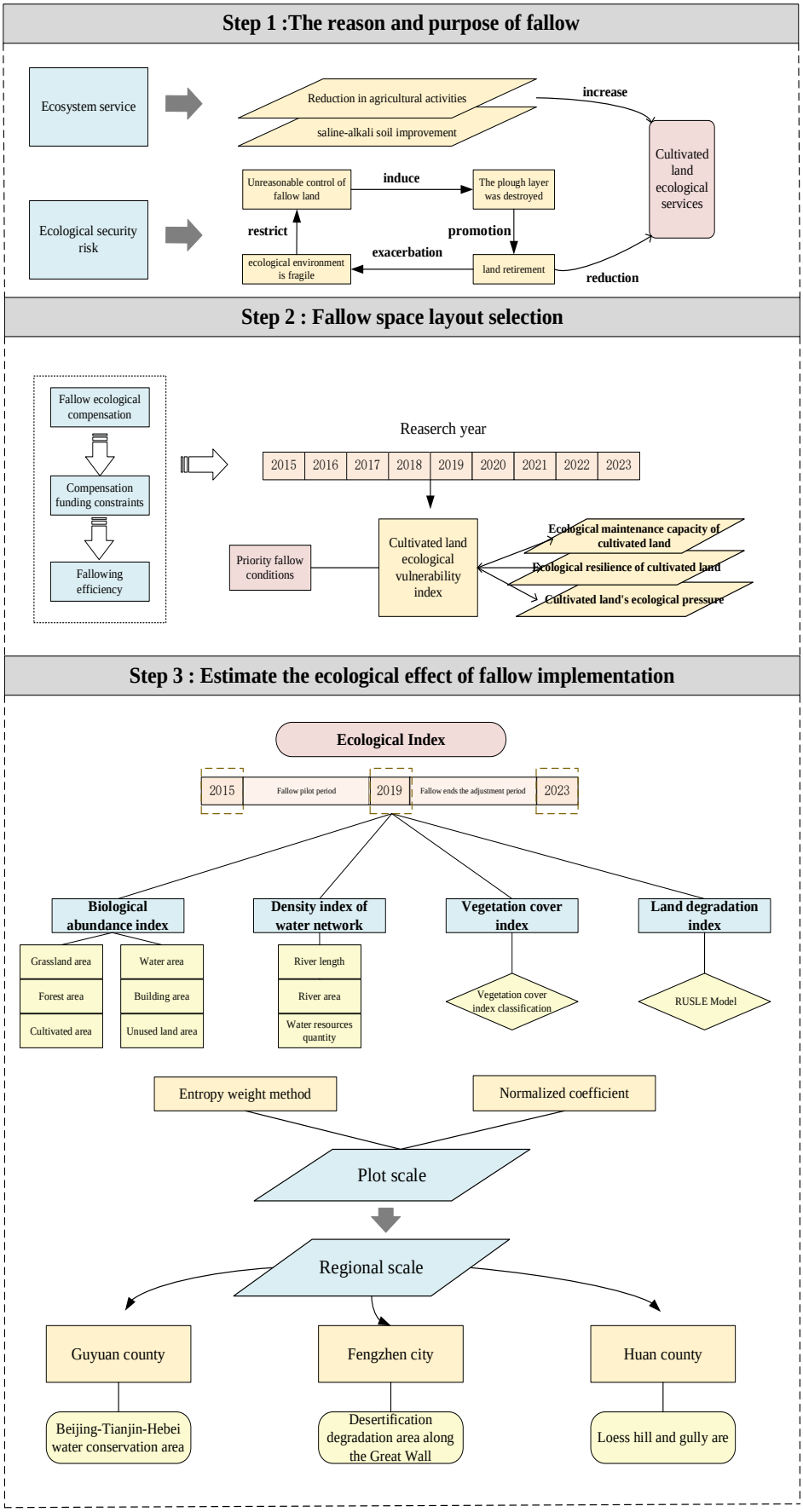

Figure 2. Research framework.

2.3.2. Study Methods

(1) Construction of Indicator System of Cultivated Land Ecological Vulnerability

Based on the characteristics of cultivated land use and the ecological environment within the agro-pastoral ecotone of northern China, an index system has been developed to assess the cultivated land's ecological vulnerability. This system encompasses three primary dimensions: Ecological Maintenance of Cultivated Land (EAOCL), Ecological Resilience of Cultivated Land (EROCL), and Ecological Pressure on Cultivated Land (EPOCL) (Table 1).

For EAOCL, indicators such as irrigation conditions [28], soil salinization levels [29], effective soil thickness [30] and topographic slope [31] are utilized to reflect both natural and anthropogenic factors influencing ecological function maintenance in the region. Previous research has established EROCL indicators that encompass societal [32], ecological [33], and environmental [34] dimensions. In constructing the EROCL index, per capita grain yield and grain yield per unit area are employed as proxies for assessing the utilization of cultivated land, with stable and continuous yields indicating favorable resilience of the cultivated land. Additionally, the soil texture, organic carbon content, and soil pH serve as indicators of the natural quality and utilization potential of cultivated soils, suggesting high productivity potential. Annual rainfall and forest coverage are used to gauge ecosystem integrity. EPOCL is primarily driven by the interference of various human activities on the cultivated land ecosystem. The greater the degree of such interference, the more pronounced the ecological degradation of cultivated land [35]. This paper constructs the index layer for EPOCL from three perspectives: population, economy, and society [28,36].

Table 1. Ecological vulnerability assessment index system of the agro-pastoral ecotone of northern China.

Goal	Criterion	Indicator	Index Definition	Implication	Influence
Ecological vulnerability diagnosis of cultivated land	Ecological sustainability of cultivated land	Irrigation conditions	Regional effective irrigation area/Regional crop planting area/%	The strength of cultivated land resources in response to drought conditions	+
		Soil salinization degree	Cumulative value of soluble salt in soil surface layer	Cultivated land ecological security	−
		Effective depth of soil	Types of soil layers affecting crop growth/cm	Crop growth status of cultivated land	+
		Terrain slope	Slope vertical height/Horizontal distance/°	Tillage conditions	−
	Ecological resilience of cultivated land	Per capita output of grain	Regional total grain output/Total area of cultivated land/(t/km^2)	Cultivated land food security level	+
		Grain yield per unit area	Total grain output/Total cultivated land area	Grain yield benefit of cultivated land	+
		Soil texture	Combination of Mineral Particles with Different Diameters in Soil	Soil tillage status	+
		organic carbon contents of soil	An important part of meeting the source of plant nutrients	Soil fertility level	+
		Annual precipitation	The sum of average monthly precipitation/(mm)	Regional climate status	+
		Soil pH	Soil acid-base strength	Suitable conditions for crop growth in cultivated land	+
		Percentage of forest cover	Forest area/Total land area/%	Regional ecological environment state	+

Table 1. *Cont.*

Goal	Criterion	Indicator	Index Definition	Implication	Influence
Ecological vulnerability diagnosis of cultivated land	Ecological Pressure on Cultivated Land	Population density	Regional total population/Regional land area	Population carrying pressure	–
		Rate of population growth	(population at the end of the year-population at the beginning of the year)/Annual average population	The driving effect of labor force growth on land ecosystem	–
		Proportion of cultivated land area	Regional cultivated land area/total land area	cultivated land change	–
		Farmers' per capita income	Farmers' income level/(yuan/person)	Degree of cultivated land input	+
		Unit fertilizer application amount	Total amount of agricultural chemical fertilizer application/Total cultivated land area/(t/km^2)	Agricultural non-point source load pollution	–
		Unit plastic film usage	Total amount of agricultural chemical fertilizer application/Total cultivated land area/(t/km^2)		–

This research is based on the classification standards of China's topography and geomorphology, with quantitative values derived for the actual slope within the study area. Quantitative assessments of irrigation conditions, soil salinization levels, effective soil layer thickness, soil organic carbon content, and soil pH are based on county-level agricultural land classification and grading protocols, along with results of cultivated land quality assessment specific to the agro-pastoral ecotone of northern China. The specific quantitative standards are detailed in Table 2.

Table 2. Classification criteria of cultivated land ecological vulnerability assessment indicators.

Indicator	Quantitative Criteria of Indicators				
	0	**0.25**	**0.5**	**0.75**	**1**
Irrigation conditions	Non-irrigation	-	General meet	Basically meet	Fully meet
Soil salinization degree	Severe salinization	moderate salinization	Mild salinization	-	No salinization
Effective soil layer thickness (cm)	0~30	-	30~50	-	>50
Terrain slope (°)	>25°	15~25°	10~15°	5~10°	0~5°
Soil texture	Mineral loam		medium loam		loam
Soil organic carbon content (g/kg)	0~0.2	0.2~0.6	0.6~1.2	1.2~2.0	>2.0
Soil pH	0~4.0, 9.0~10.0	4.0~5.0	5.0~5.5, 8.5~9.0	5.5~6.5, 7.5~8.5	6.5~7.5

Range standardization is employed to nondimensionalize the selected indicators, enabling a more coherent analysis. Regardless of whether the index values are positive or negative, the transformed values are standardized to fall within the interval of [0, 1], where 1 represents the optimal condition, and 0 signifies the worst condition. The specific calculation formula is as follows:

Positive indexes:

$$P_{ij} = \left(X_{ij} - X_{jmax}\right) / \left(X_{jmax} - X_{jmin}\right) \quad (1)$$

Negative indicators:

$$P_{ij} = \left(X_{jmax} - X_{ij}\right) / \left(X_{jmax} - X_{jmin}\right) \quad (2)$$

In the formula, X_{ij} denotes the original value of the j-th index in the i-th year; P_{ij} represents the standardized value of the j-th index in the i-th year; and X_{jmax} and X_{jmin} refer to the maximum and minimum values of the j-th index, respectively.

(2) Determining the Index Weight

This research employs the entropy weight method, an objective weighting approach [37,38], to ascertain the relative importance of the 17 indicators within the diagnostic index system for ecologically fragile cultivated land in the agro-pastoral ecotone of northern China. To ensure the robustness of the entropy values, a unit conversion protocol is implemented.

The specific steps are as follows:

Proportional conversion of indicators:

$$S_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}} \quad (3)$$

Calculate the entropy of the index:

$$h_i = -\sum_{i=1}^{n} S_{ij} ln S_{ij} \quad (4)$$

Reverse the entropy value:

$$f_j = 1 - h_j \quad (5)$$

Get the weight:

$$w_j = \frac{f_j}{\sum_{j=1}^{m} f_{ij}} \quad (6)$$

where X_{ij} represents the jth index value of sample i (i = 1, 2,. . . n; j = 1, 2,. . . m), n the number of samples, and m the number of indicators.

(3) Calculation of Ecological Vulnerability Index of Cultivated Land

In this research, the integrated index approach is utilized to derive the ecological vulnerability index of cultivated land. Simultaneously, the geographic information analysis capabilities of ArcGIS 10.8 are employed to score ecologically fragile cultivated lands, resulting in the calculation of the ecological vulnerability value for cultivated land in the agro-pastoral ecotone of northern China. The calculation formula is as follows:

$$F = \sum_{i=1}^{m} W_i \times X_i \quad (7)$$

In the formula, F is the ecological vulnerability index value of cultivated land, and the value range of F is constrained between [0, 1]. W_i is the standardized value of each index, and X_i is the relative weight of each index,

(4) Determination Method of Fallow Land Area

Following the calculation of the ecological vulnerability index based on the 'maintenance-resilience-pressure' framework, different states of cultivated land vulnerability are expressed in graded levels, which serve as the basis for choosing and delineating fallow areas. Drawing on both domestic and international literature sources, this paper employs the equal interval division method to classify cultivated land into four categories: extremely fragile, more than fragile, relatively fragile, and generally fragile, based on the environmental characteristics and regional conditions of the study area. It is important to note that while the 'generally fragile' category of cultivated land currently poses no immediate threat of degradation, it is designated as a reserve resource to ensure the ecological security of cultivated lands in the region. Additionally, the evaluation results pertaining to the cultivated land ecological vulnerability across various areas in the region exhibit a degree of relativity; the specific grading of cropland ecological vulnerability and the zoning of fallow spaces are presented in Table 3.

Table 3. Fallow space zoning standards based on cultivated land degradation status.

Ecological Fragile State of Cultivated Land	Synthesis Diagnostic Index	State Feature	Zoning of Fallow Space
Generally vulnerable	[0, 0.45)	The function of cultivated land ecosystem is complete, and there is almost no ecological problem. The ecological function maintenance and ecological resilience of cultivated land are high, the ecological pressure of cultivated land is small, and there is no ecological degradation.	Prohibited fallow area
More vulnerable	[0.45, 0.55)	The cultivated land ecosystem is basically intact, facing the problem of mild land desertification and salinization. The ecological function maintenance and ecological resilience of cultivated land are high, the ecological pressure of cultivated land is small, and the incidence of ecological degradation is small.	Restricted fallow area
Very vulnerable	[0.55, 0.65)	The ecological system of cultivated land has been degraded, and natural disasters such as land salinization, land desertification and drought often occur. The ecological function maintenance and ecological resilience of cultivated land are suboptimal, the ecological pressure of cultivated land is high, and the phenomenon of moderate cultivated land degradation appears.	Sub-priority fallow area
Extremely vulnerable	[0.65, 1]	The function of cultivated land ecosystem is missing, soil desertification and soil erosion are serious, natural disasters such as drought and sand storm occur frequently, the ecological function maintenance and ecological resilience of cultivated land are deficient, the ecological pressure of cultivated land is high, and the cultivated land is severely degraded.	Priority fallow area

(5) Ecological effect evaluation of fallow implementation

This research selected representative fallow modes from three distinct regions within the northern farming-pastoral ecotone, focusing on counties (or districts) officially classified as fallow areas, to analyze the ecological effects before and after fallowing. This study employs the Ecological Index (EI) to assess the ecological effects of fallowing. The Ecological Index reflects the richness or scarcity of biodiversity within the evaluated area, the level of vegetation coverage, the abundance of water resources, the intensity of environmental stressors, and the pressure of pollutants being carried. Furthermore, it incorporates the ecological destruction and environmental pollution events that severely impact the safety of human habitation and production within the region, thereby limiting and regulating the status of the ecological environment. This can be regarded as a comprehensive indicator of the interrelated and coordinated development of multiple ecological environmental factors. The evaluation index was based on the Technical Specification for Ecological Quality Assessment established by the China Environmental Protection Administration in 2006. This study extracted four types of environment-related factors using remote sensing data. Environmental changes in Guyuan County (located in the Beijing–Tianjin–Hebei water conservation area) were compared and analyzed before the implementation of the fallow policy (2015), during its implementation (2019), and after its implementation (2023). Similarly, environmental changes in Fengzhen City (characterized by loess hilly and gully terrain) and Huan County were also evaluated.

The calculation formula of the Ecological Index (EI) is as follows:

$$EI = \sum_{i=1}^{n} B_i K_i = 0.30B_1 + 0.20B_2 + 0.25B_3 + 0.25B_4 B_1 = Abio \times \begin{pmatrix} 0.35 \times Forest + 0.21 \times Glassland + 0.28 \times Water + 0.11 \times Cropland \\ +0.04 \times Construction\ land + 0.01 \times Unutilized \end{pmatrix} / Area$$

$$B_2 = Ariv \times River\ length / Area + Ariv \times River\ area / Area + Ariv \times Water\ resources\ quantity / Area$$

$$B_3 = Aveg \times \begin{pmatrix} 0.5 \times High\ coverage\ index + 0.3 \times Medium\ coverage\ index \\ +0.2 \times Low\ coverage\ index \end{pmatrix}$$

$$B_4 = Aero \times \begin{pmatrix} 0.3 \times Micro\ ersion\ Area + 0.25 \times Light\ erosion\ Area + 0.2\times \\ Middle - extent\ erosion\ Area + 0.1 \times Intensive\ erosion\ Area \\ +0.1 \times More\ intensive\ erosion + 0.05 \times Severe\ erosion\ Area \end{pmatrix}$$

where k represents the corresponding weight assigned to the index, B_i represents the Ecological Index, B_1 denotes the biological abundance index, B_2 indicates the water network density index, B_3 refers to the vegetation cover index, and B_4 signifies the Soil conservation index. *Abio*, *Ariv*, *Aveg*, and *Aero* are the normalized coefficients of each Ecological Index, respectively, and the specific array is listed in Table 4.

Table 4. Normalized coefficient criteria.

Normalized Coefficient	Value
Biological abundance index	400.62
Vegetation cover index	355.24
River length	46.63
Water resources quantity	61.42
River area	17.88
Soil conservation index	146.33

(6) RUSLE Model

In Method (5), the areas of various degrees of soil erosion calculated for the Aero index are derived using the RUSLE model. The Revised Universal Soil Loss Equation (RUSLE) is widely utilized globally for soil erosion assessment [39]. Based on this, this paper uses the model to evaluate the amount of soil erosion before and after fallow. The specific formula is:

$$B = R \times K \times LS \times C \times P \quad (8)$$

In the formula, B is the soil erosion modulus [t/(hm^2·a)]; R is rainfall erosivity factor [(MJ·mm·hm^2)/(h·a)]; K is a soil erodibility factor [(t·hm^2·h)/(hm^2·MJ·mm)]; LS is the slope length and slope factor; C is vegetation cover index and management factor; P is the factor of soil and water conservation measures. This research employs the RUSLE model to calculate soil erosion intensity for three fallow counties in 2015, 2019, and 2023, categorizing soil erosion into six levels according to the "(SL190-2007) Soil Erosion Classification Standard" [40].

3. Results

3.1. Comprehensive Diagnosis Results of Cultivated Land Vulnerability in Farming-Pastoral Ecotone of Northern China

3.1.1. Time Variation Characteristics

Between 2015 and 2023, the ecological vulnerability index of cultivated land in the agro-pastoral ecotone of northern China exhibited a U-shaped trend, characterized by an initial decrease followed by a subsequent increase. With the exception of the Beijing–Tianjin–Hebei water conservation area, the ecological vulnerability index in the ecotone and other regions reached its lowest point in 2019, after which a general upward trajectory was observed. Overall and regional ecological vulnerability improved from 'extremely fragile' in 2015 to 'relatively fragile' in 2017, maintaining stability thereafter. The year 2019 marked the conclusion of the country's three-year fallow pilot program. Following this, grain cultivation has gained a comparative advantage, leading to potential risks of 'fallow without cultivation' or land abandonment during the later stages of the fallow period, exacerbated by the imbalance in income and expenditure related to grain production. Moreover, for fallow lands with high accessibility and fertile soils, there exists a risk of excessive utilization. In efforts to maximize land productivity, farmers may engage in "retaliatory" utilization after the fallow period, increasing output per unit area and potentially reinstating a detrimental cycle of soil hardening and fertility decline (Figure 3).

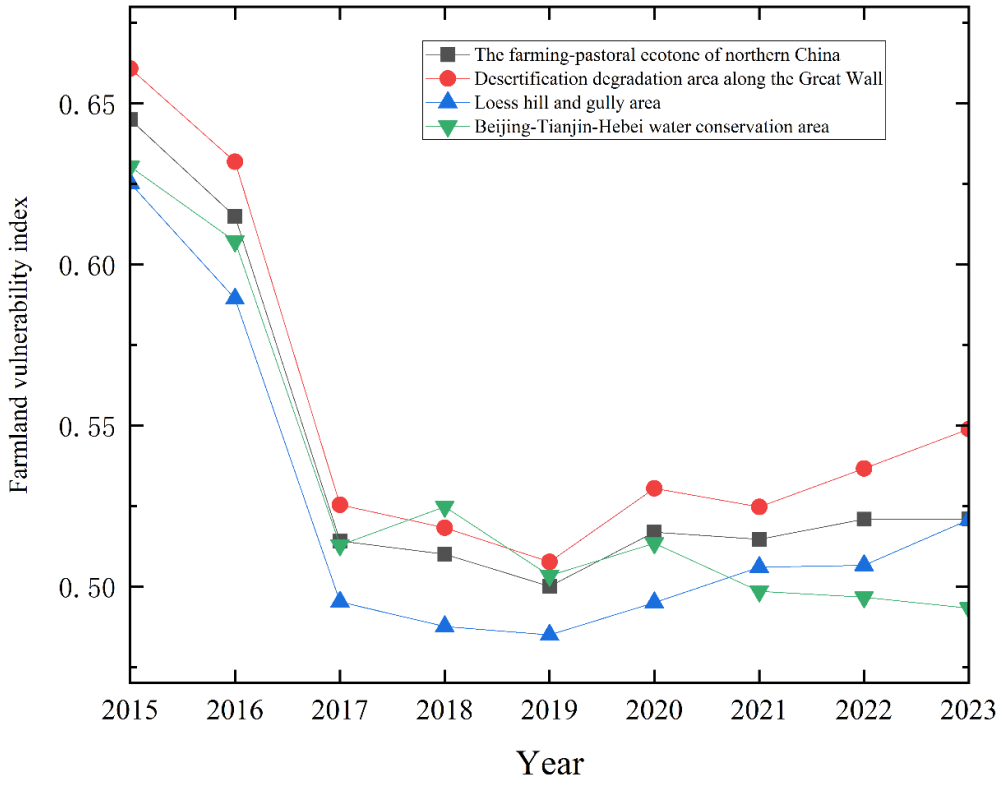

Figure 3. The farmland vulnerability index in the agro-pastoral ecotone of northern China.

3.1.2. Spatial Differentiation Characteristics

The cultivated land vulnerability index during 2015–2023 was spatially visualized to illustrate the spatial variations and evolutionary characteristics (Figure 4). The comprehensive scores of cultivated land ecosystems in 145 counties (including districts) in the agro-pastoral ecotone of northern China ranged from 0.3378 to 0.7914.

(1) The cultivated land vulnerability in the agro-pastoral ecotone of northern China exhibits pronounced spatial heterogeneity. Between 2015 and 2016, areas classified as extremely fragile were widely distributed, predominantly concentrated in the northern and central regions. From 2017 to 2023, the ecological vulnerability pattern of cultivated land stabilized, characterized by overall consistency with localized fluctuations. While most areas remained relatively fragile, the ecological vulnerability pattern in the region after 2020 indicated a general deterioration compared to 2019.

(2) Regions exhibiting comparable levels of cultivated land ecological vulnerability demonstrate spatial clustering. Areas with similar ecological vulnerability levels show a contiguous distribution. Notably, in 2015, Chifeng City, Ulanqab City, Xinzhou City, and other counties were classified as extremely vulnerable in terms of cultivated land ecology. These areas not only share proximity in both external and internal spatial contexts but also exhibit similar characteristics in terms of ecological fragility across various years.

(3) The number of counties and cities exhibiting various degrees of vulnerability, along with the proportional area they occupy, generally reflects a trend of 'low-in and high-out'. In 2015, the area classified as 'extremely vulnerable' and 'very vulnerable' cultivated land in the northern farming-pastoral ecotone accounted for 55.08% and 39.66%, respectively, with the number of affected counties being 71 and 68. The overall degree of cultivated land ecological vulnerability remains a concern. By 2017, for the first time, the number of counties classified as 'extremely vulnerable' and the proportion of cultivated land area within the entire region fell to zero. Since then, by 2023, the proportion of 'relatively vulnerable' and 'generally vulnerable' cultivated land areas has shown an increasing trend, while the proportion of "very vulnerable" cultivated land and the number of affected counties have consistently represented the largest share. Thus, the protection of cultivated land is of urgent necessity. The overall evolutionary trend indicates a gradual contraction of areas with high ecological vulnerability indices in cultivated land, accompanied by an expansion of areas with low vulnerability (Table 5).

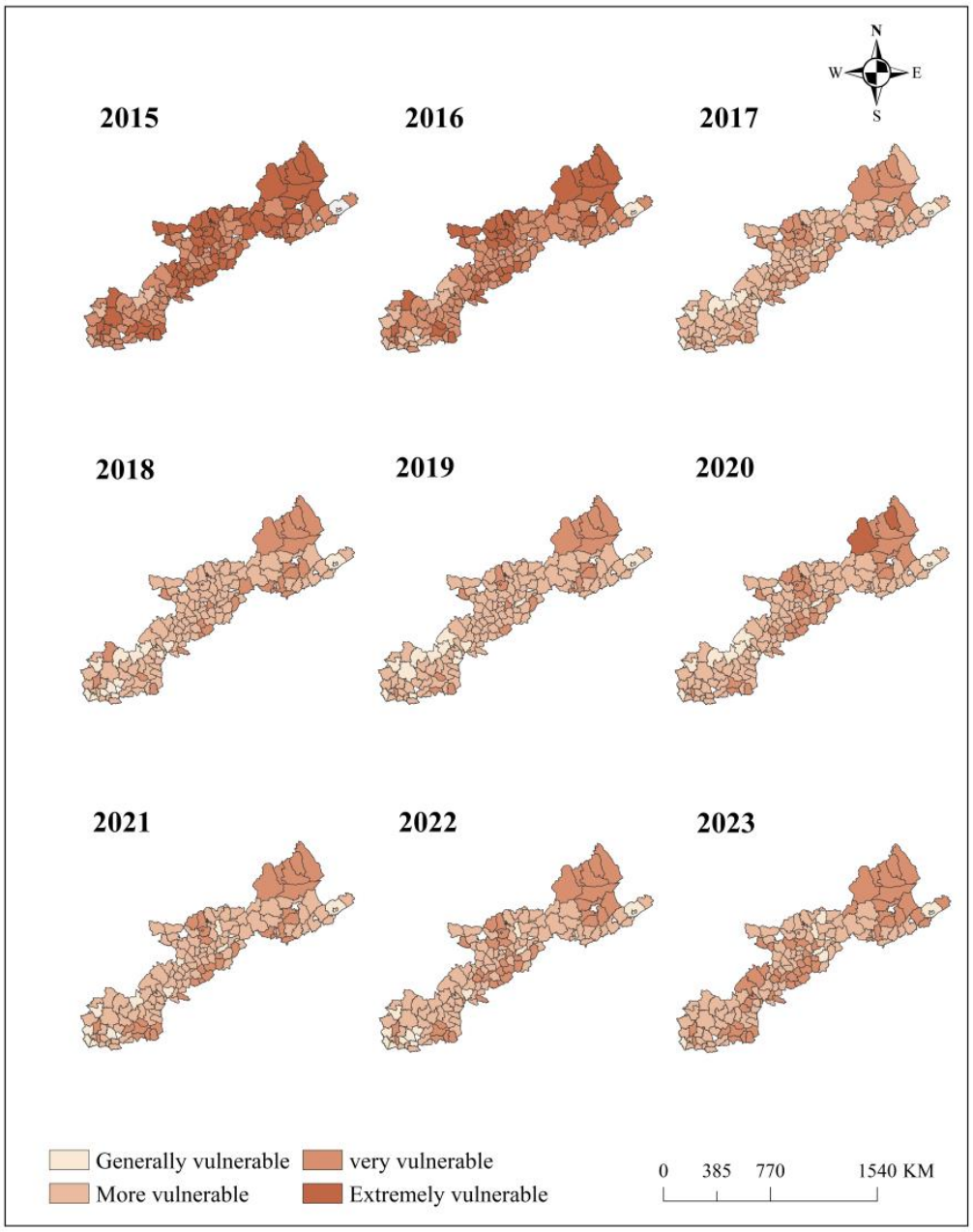

Figure 4. Ecological vulnerability index of cultivated land in the agro-pastoral ecotone of northern China during 2015–2023.

Table 5. The fragile situation of cultivated land ecosystems in the farming-pastoral ecotone of northern China.

Year	Area	Extremely Vulnerable			Very Vulnerable			More Vulnerable			Generally Vulnerable		
		Number of County	Vulnerable Arable Land Area	Proportion	Number of County	Vulnerable Arable Land Area	Proportion	Number of County	Vulnerable Arable Land Area	Proportion	Number of County	Vulnerable Arable Land Area	Proportion
		Number	$\times 10^4$ km^2	%	Number	$\times 10^4$ km^2	%	Number	$\times 10^4$ km^2	%	Number	$\times 10^4$ km^2	%
2015	a	48	18.39	39.14	26	7.45	15.85	2	0.94	2	1	0.62	1.32
	b	9	3.82	8.13	28	7.47	15.89	2	0.79	1.67	0	0	0
	c	14	3.67	7.81	14	3.72	7.92	1	0.03	0.07	0	0	0
2016	a	31	14.73	31.34	42	10.50	22.34	3	1.65	3.51	1	0.62	1.32
	b	6	2.30	4.89	27	6.86	14.60	11	2.91	6.19	0	0	0
	c	0	0	0	22	7.21	15.34	2	0.22	0.46	0	0	0
2017	a	0	0	0	26	11.22	23.87	47	14.02	29.84	5	2.26	4.8
	b	0	0	0	4	0.87	1.86	37	10.23	21.76	2	0.4	0.86
	c	0	0	0	4	1.47	3.13	19	5.77	12.27	2	0.75	1.6
2018	a	0	0	0	15	9.07	19.3	57	15.87	33.78	5	2.55	5.43
	b	0	0	0	4	1.74	3.7	32	8.25	17.57	8	2.08	4.43
	c	0	0	0	5	1.67	3.55	19	5.76	12.25	0	0	0
2019	a	0	0	0	14	9.05	19.25	57	15.19	32.32	6	3.26	6.94
	b	0	0	0	4	0.87	1.86	35	9.9	21.06	5	1.3	2.77
	c	0	0	0	2	0.65	1.37	21	6.59	14.03	1	0.18	0.39
2020	a	2	2.71	5.77	26	10.41	22.16	44	11.41	24.28	5	2.96	6.3
	b	0	0	0	4	1.06	2.27	37	10.04	21.36	3	0.97	2.07
	c	0	0	0	2	0.31	0.66	21	6.93	14.74	1	0.18	0.39
2021	a	0	0	0	20	10.36	22.05	53	15.54	33.07	4	1.60	3.4
	b	0	0	0	9	2.41	5.12	30	8.06	17.15	5	1.6	3.41
	c	0	0	0	4	1.14	2.42	17	5.81	12.36	3	0.48	1.01
2022	a	0	0	0	30	16.34	34.77	45	12.91	27.47	2	0.92	1.96
	b	0	0	0	8	1.86	3.96	28	8	17.03	8	2.21	4.7
	c	0	0	0	1	0.28	0.6	20	6.67	14.18	3	0.48	1.02
2023	a	0	0	0	39	33.46	34.1	37	30.44	31.02	1	3.18	3.24
	b	0	0	0	13	2.33	2.37	30	17.45	17.78	1	0.98	1
	c	0	0	0	1	0.36	0.37	19	7.033	7.71	4	4.34	4.42

Note: a stands for Desertification degradation area along the Great Wall; b stands for Loess Hill and Gully area; c stands for Beijing–Tianjin–Hebei water conservation area.

3.2. Spatial Layout Results of Fallow Area in Northern Farming-Pastoral Ecotone

Based on the classification of the ecological vulnerability index for cultivated land within the agro-pastoral ecotone of northern China, a zoning map of fallow areas during 2015–2023 was generated (Figure 5). First-level fallow counties are characterized by insufficient agricultural infrastructure and fragile ecological environments, rendering them susceptible to soil erosion, land desertification, and salinization. Given the critical need for soil fertility restoration and ecological protection, these regions have been designated as priority fallow areas. Second-level fallow counties exhibit suboptimal natural conditions for agriculture, deficient agricultural infrastructure, and challenges such as desertification, salinization, and overutilization. These areas contain a higher proportion of low-yielding fields and inferior-quality cultivated land, leading to their classification as sub-priority fallow areas. Third-level fallow counties demonstrate improved ecological conditions, reduced risks of land degradation, more favorable agricultural conditions, and fewer anthropogenic obstacles. Consequently, these areas necessitate planned fallow implementation and are classified as restricted fallow areas. Fourth-level fallow counties feature high-quality cultivated land, favorable ecological conditions, well-developed agricultural infrastructure, and currently face no significant risk of land degradation. These regions are recognized as primary grain-producing areas and are therefore classified as prohibited fallow areas.

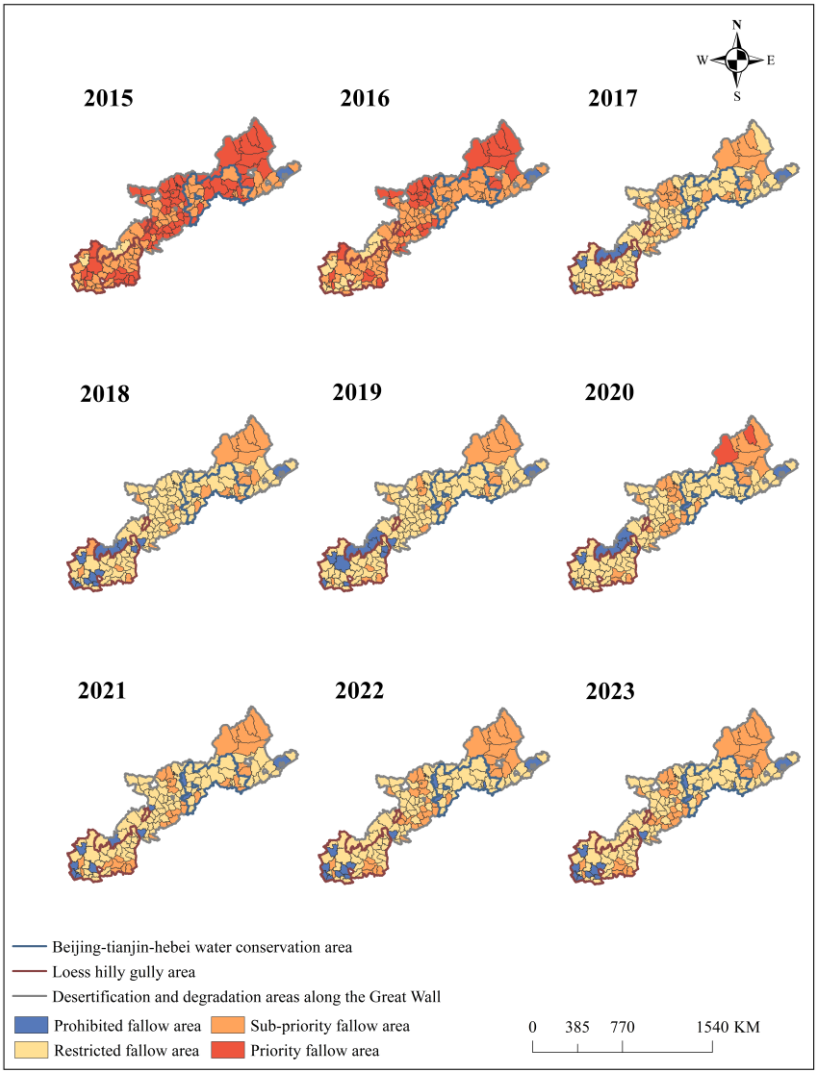

Figure 5. Fallow space zoning map of the farming-pastoral ecotone of northern China during 2015–2023.

Spatial analysis reveals widespread ecological degradation across all three regions of the agro-pastoral ecotone in northern China during 2015–2016, with this degradation distributed throughout the entire area. Between 2017 and 2023, areas necessitating fallow implementation were predominantly located in the desertification zones along the Great Wall and within the loess hilly and gully regions. The desertification area adjacent to the Great Wall is characterized by poor cultivated land quality and low levels of agricultural modernization, representing a cold spot for the grain yield per unit area in the agro-pastoral ecotone of northern China [41]. The loess hilly and gully region, while possessing a long history of agricultural activity and a robust agricultural foundation, faces significant challenges due to its location within the Mu Us Sandy Land. This area grapples with a harsh ecological environment, low vegetation cover index, frequent droughts, and severe land fragmentation, all of which collectively constrain local agricultural development.

By comparing the fallow counties published by the government with those divided in this paper, the results indicate a high degree of spatial concordance between the officially designated fallow pilot counties and those predicted by our model, with clustered distributions primarily observed in the northern, central, and southern parts of the region. Areas of discrepancy predominantly align with regions undergoing ecological restoration projects, such as the conversion of farmland to forest and grassland. This methodology

demonstrates substantial practical efficacy in predicting and optimizing the distribution of fallow land (Figure 6).

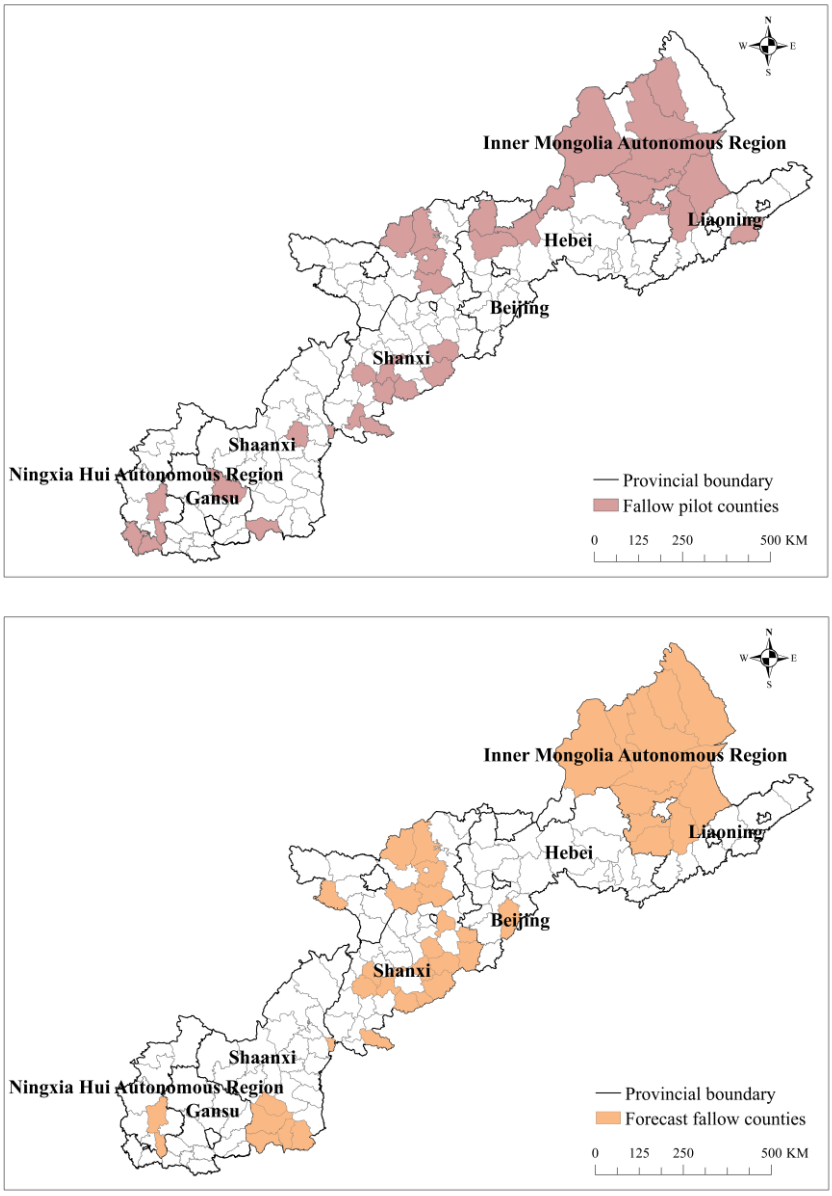

Figure 6. Comparison of fallow pilot area distribution and fallow prediction county distribution.

3.3. Evaluation of Ecological Effect of Fallow Land in Northern Farming-Pastoral Ecotone

Figure 7 illustrates the geographical locations of typical fallow counties. This study conducts an assessment of the ecological effects of fallowing in these three counties.

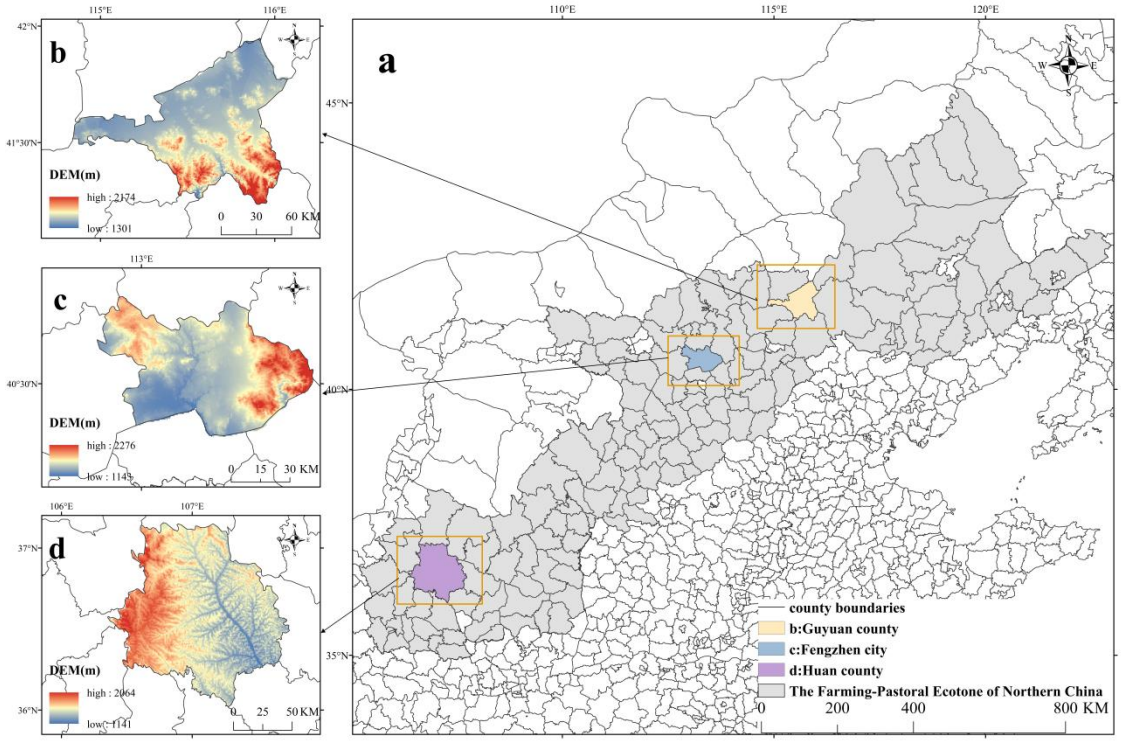

Figure 7. Fallow County zoning map. (**a**) the agro-pastoral ecotone of northern China. (**b**) Guyuan county. (**c**) Fengzhen city. (**d**) Huan county.

3.3.1. Analysis of Ecological Index Change in Fallow Counties

According to the above calculation, the final extracted Ecological index is shown in Table 6.

Table 6. Ecological index of fallow county from 2015 to 2023.

Area	Year	Biological Abundance Index	Water Network Density Index	Vegetation Cover Index	Soil Conservation Index
Guyuan county	2015	62.63	27.82	37.15	39.35
	2019	66.71	28.37	40.76	40.66
	2023	63.41	30.42	40.13	39.52
Fengzhen city	2015	69.46	21.32	35.6	37.81
	2019	72.31	23.41	38.82	39.69
	2023	70.43	22.8	37.5	38.28
Huan county	2015	71.95	11.26	17.04	19.92
	2019	73.62	14.61	24.27	29.45
	2023	74.84	12.76	21	24.80

3.3.2. Analysis of Changes in the Biological Abundance Index

The bioabundance index of Guyuan County and Fengzhen City exhibited an initial increase followed by a subsequent decrease during 2015–2023. In contrast, the bioabundance index of Huan County demonstrated a consistent upward trend, resulting in an overall index that was higher than those of Guyuan County and Fengzhen City. This discrepancy is primarily attributed to the significant influence of woodland and grassland areas on the regional vegetation abundance index. Between 2015 and 2023, the areas of arable land, forest land, and grassland in Guyuan County and Fengzhen City exhibited similar trends,

characterized by a continuous increase in cropland and forest areas alongside a persistent decline in grassland. Notably, Huan County experienced significant fluctuations in cropland areas, initially showing an upward trend followed by a downward shift. Following the conclusion of the national fallow policy, Guyuan County and Fengzhen City initiated a new round of fallow measures. Consequently, changes in land use across different time periods began to align. It is evident that during the fallow pilot phase, the areas of arable land in all three counties exhibited an upward trend (Table 7, Figure 8).

Table 7. Changes and proportion of land use types in fallow counties during 2015–2023.

	Types of Land	2015		2019		2023	
		Area/km^2	Proportion/%	Area/km^2	Proportion/%	Area/km^2	Proportion/%
Guyuan county	Cropland	1203.14	37.56	1310.51	40.91	1361.45	42.50
	Forest	179.98	5.62	212.88	6.65	223.41	6.97
	Shrub	0.06	0.002	0.03	0.001	3.02	0.09
	Grassland	1774.34	55.39	1626.87	50.79	1551.35	48.43
	Water	19.90	0.62	19.12	0.60	22.30	0.70
	Barren	0.47	0.01	0.73	0.02	0.98	0.03
	Impervious	25.38	0.79	33.15	1.03	39.05	1.22
Fengzhen city	Cropland	1053.68	38.12	1128.69	40.84	1144.64	41.41
	Forest	79.43	2.87	90.13	3.26	100.47	3.63
	Shrub	0.09	0.003	0.05	0.002	0.05	0.002
	Grassland	1571.73	56.87	1478.36	53.49	1443.92	52.24
	Water	1.18	0.04	1.91	0.07	1.65	0.06
	Barren	0.06	0.002	0.17	0.01	0.15	0.01
	Impervious	57.70	2.09	64.59	2.34	71.55	2.59
Huan county	Cropland	1242.24	13.06	1349.43	14.19	1160.43	12.20
	Forest	3.58	0.04	6.40	0.07	29.83	0.31
	Grassland	8250.50	86.76	8137.39	85.57	8297.82	87.26
	Water	0.16	0.002	0.16	0.002	0.21	0.002
	Barren	1.67	0.02	4.22	0.04	4.24	0.04
	Impervious	11.49	0.12	12.05	0.13	13.74	0.14

From 2015 to 2023, land use transitions among arable land, grassland, and forest land in Guyuan County and Fengzhen City were notably active. In Guyuan County, 162.24 km^2 of grassland was continuously converted to arable land during this period, accounting for 5.07% of the total grassland area, while 59.98 km^2 was converted to forest land, representing 18.73%. Fengzhen City exhibited similar trends in land use changes, with grassland consistently transitioning to both arable land and forest land, primarily shifting to arable land during 2015–2023. In contrast, land use changes in Huan County during the same period were characterized by reciprocal transitions between grassland and arable land, with the arable land area displaying a "first increase and then decrease" trend. From 2015 to 2019, 106.71 km^2 of grassland was converted to arable land in Huan County, accounting for 1.13% of the total grassland area. Conversely, from 2019 to 2023, 187.25 km^2 of arable land was converted back to grassland, representing 1.97%, alongside 23.3 km^2 of grassland being converted to forest land. This pattern is closely related to Huan County's current emphasis on developing high-standard farmland and implementing national land greening pilot demonstration projects, which included the initiation of grassland and forest vegetation restoration projects in 2023 (Figure 9).

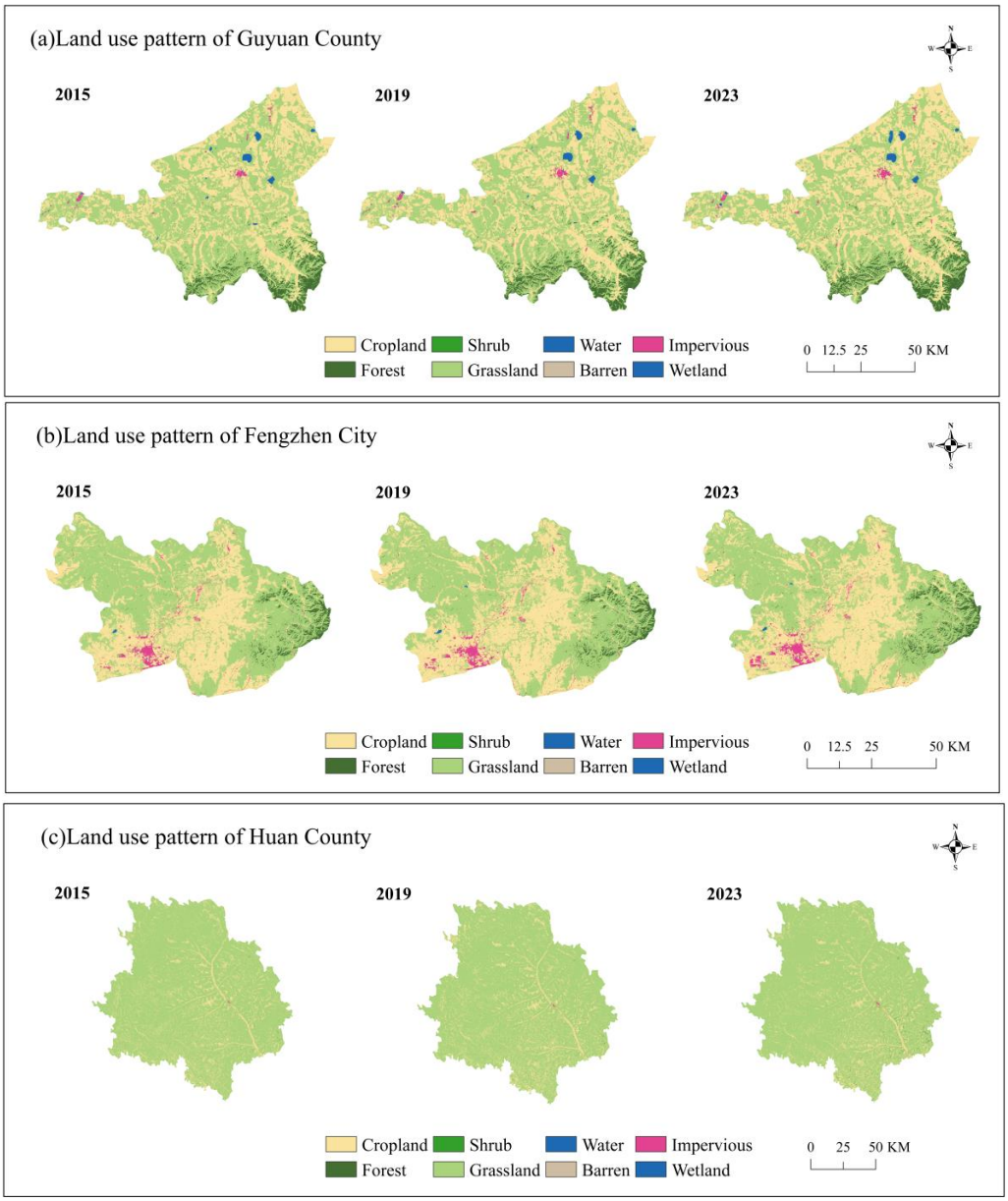

Figure 8. Spatial distribution of land use in fallow counties during 2015–2023.

3.3.3. Analysis of Changes in the Density Index of the Water Network

The water network density index of Guyuan County, situated in the Beijing–Tianjin–Hebei water conservation area, was higher than that of the other counties, exhibiting a gradual upward trend. Both the forested and water areas in Guyuan County have shown an increasing trend, indicating improved soil and water conservation capabilities following the first round of fallowing. In contrast, the water network density indices for Fengzhen City and Huan County displayed a slight downward trend after 2019. Notably, Huan County, located in the loess hilly gully area, suffers from significant evaporation and poor hydrological conditions, resulting in a relatively low overall water network density index.

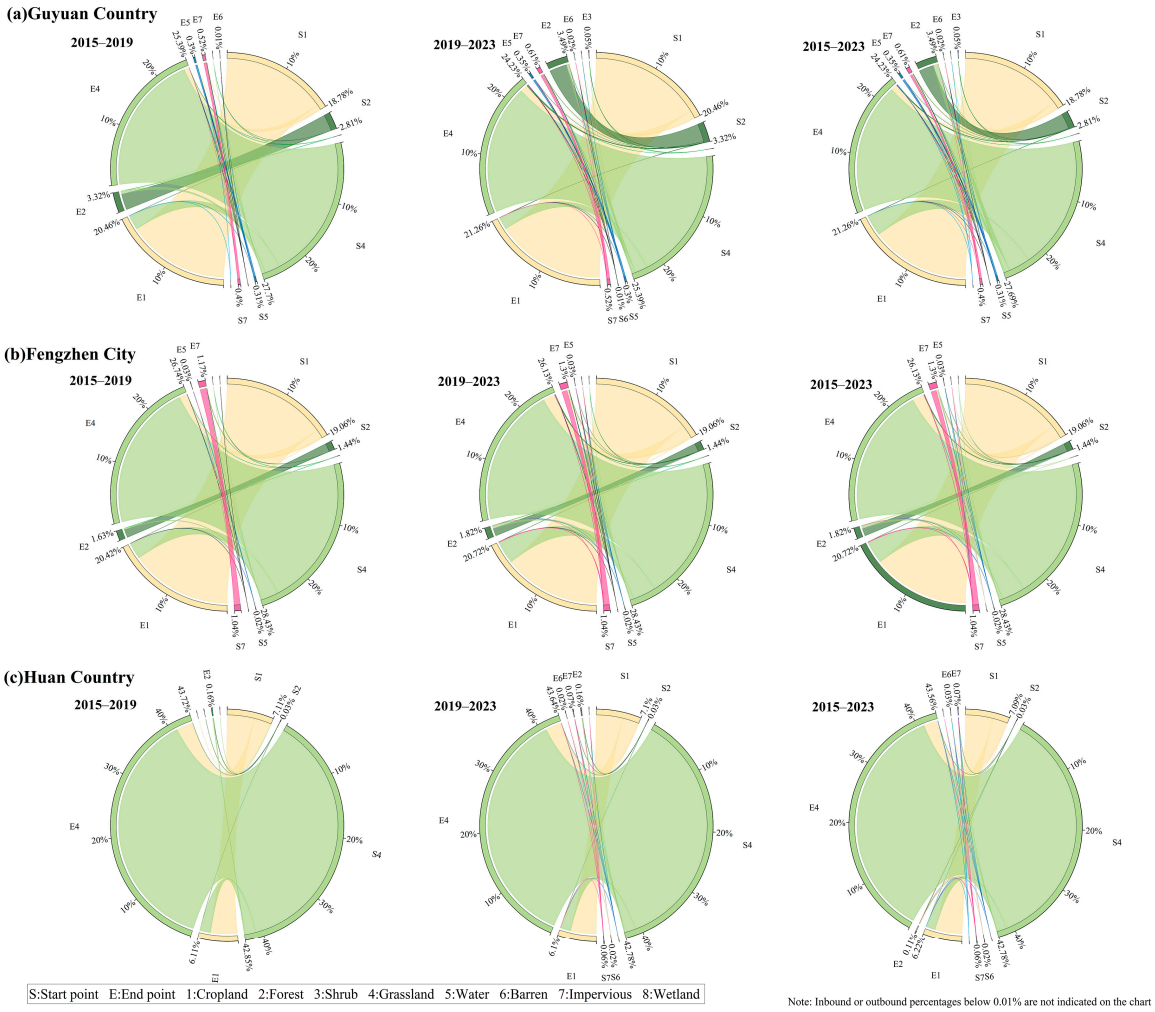

Figure 9. String map of land transfer in fallow counties during 2015–2023.

3.3.4. Analysis of Changes in the Vegetation Cover Index

The vegetation cover index of each county was divided into four grades and analyzed spatially. The spatial distribution of vegetation cover index across the three fallow counties reveals significant heterogeneity in high and low-value areas across different periods, along with notable trends in change. Guyuan County, characterized by a temperate semi-humid continental climate with ample rainfall, provides favorable conditions for vegetation growth. From 2015 to 2023, the county maintained a generally high vegetation cover index, with a predominance of high-value areas throughout the region, except for low-value areas primarily concentrated in the western sector. In the course of this period, the central region exhibited an initial increase followed by a gradual decrease in the vegetation cover index. Fengzhen City, situated in the semi-humid and semi-arid ecotone, experiences a distinct temperate continental monsoon climate with concentrated rainfall patterns. Between 2015 and 2019, there was a substantial increase in vegetation cover index across the entire region. However, the vegetation cover index pattern subsequently stabilized, with significant fluctuations likely attributable to anthropogenic influences. Huan County, under a temperate continental monsoon climate, exhibits a relatively low overall vegetation cover index, with a marked disparity in the distribution of high and low-value areas. High-value areas are predominantly located in the southern and southeastern parts of the region, primarily within semi-humid zones conducive to vegetation growth. Conversely, low-value areas are concentrated in the northern portion of the county, characterized by limited precipitation and relatively homogeneous surface vegetation, consisting mainly of

grassland and low shrubs. While the temporal change pattern in Huan County aligns with that of the other two counties, the period from 2019 to 2023 displayed a more pronounced decline in the vegetation cover index compared to the other regions (Figure 10).

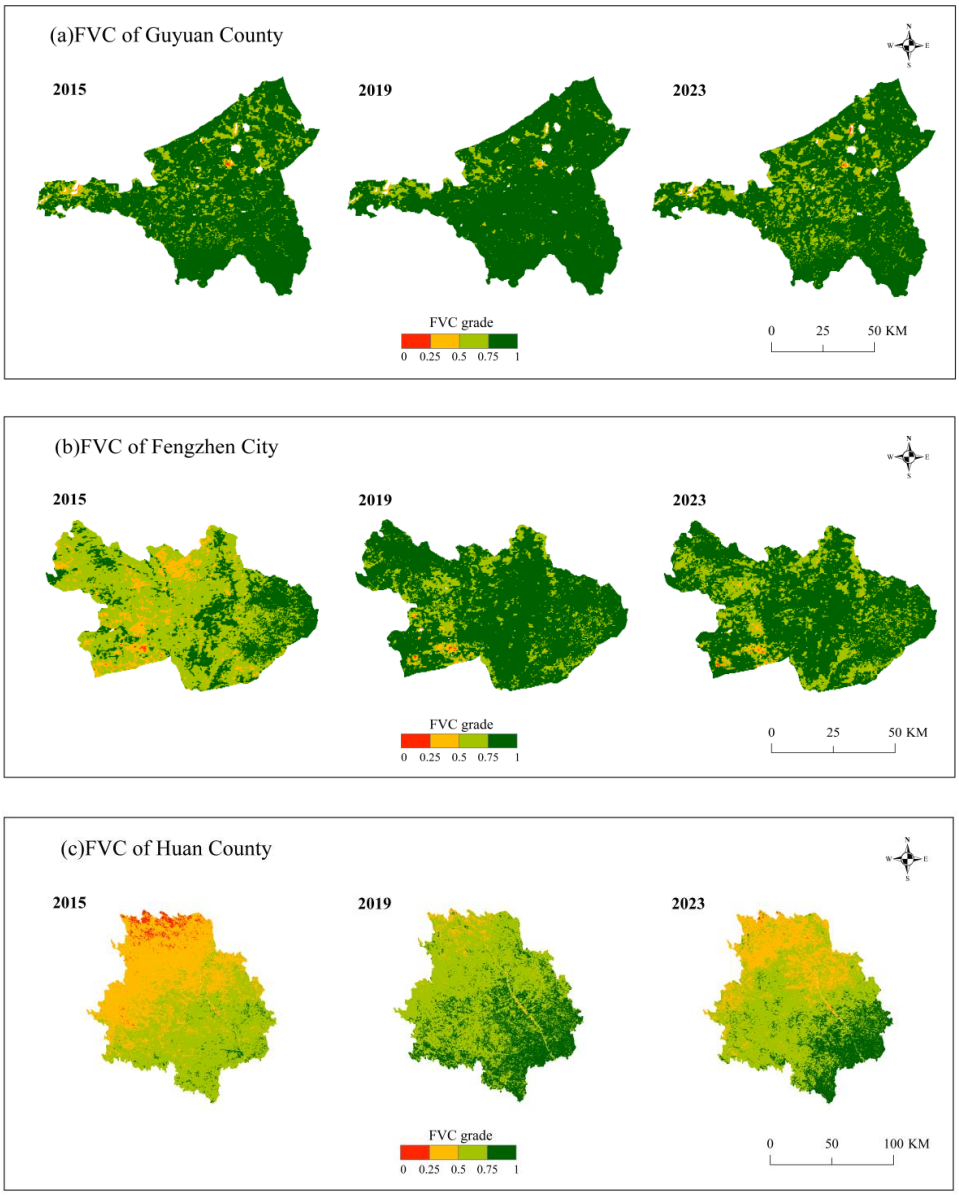

Figure 10. Spatial-temporal changes of vegetation cover index in fallow counties during 2015–2023.

3.3.5. Analysis of Changes in the Soil Conservation Index

The Soil conservation index of each county was divided into six levels, and the soil erosion area of each level was calculated and visualized in space. As indicated in Table 8, following the implementation of the fallow project, there has been a positive trend in the dynamics of soil erosion within the fallow counties. From 2015 to 2019, the area affected by slight erosion in Guyuan County increased most rapidly among all categories of erosion, totaling approximately 361.6 km^2, while the area experiencing moderate erosion decreased most significantly by about 127.3 km^2. During this period, the changes in slight, moderate, and levels of severe erosion were notably more pronounced compared to the other three categories. From 2019 to 2023, there was a slight decline in the proportion of soils affected by slight and moderate erosion, while areas of additional categories of erosion exhibited an overall increasing trend, albeit with relatively minor fluctuations. In Fengzhen City,

the extent of soil erosion varied significantly over time; between 2015 and 2019, the area under slight erosion rose by 690.61 km^2. However, by 2023, this area had decreased by 514.59 km^2. Although there has been some alleviation in soil erosion levels compared to 2015, it is crucial to investigate the underlying causes of these changes. In Huan County, the overall trend in soil erosion levels during 2015–2023 indicates a transition from areas of high erosion to areas of low erosion. Specifically, the areas of Severe erosion, more intensive erosion, and intense erosion decreased by 1.58%, 16.43%, and 16.43%, respectively, highlighting a clear trend of diminishing soil erosion (Table 8).

Table 8. Soil erosion intensity and proportion in fallow counties during 2015–2023.

Erosion Intensity	County	2015		2019		2023	
		Area/km^2	Proportion/%	Area/km^2	Proportion/%	Area/km^2	Proportion/%
Micro erosion	Guyuan county	2265.87	62.92	2627.47	72.96	2440.25	67.77
	Fengzhen city	1238.89	45.51	1929.49	70.88	1414.91	51.98
	Huan county	322.32	3.49	2182.02	23.63	1625.29	17.60
Light erosion	Guyuan county	791.66	21.98	836.60	23.23	803.43	22.31
	Fengzhen city	1072.13	39.39	411.84	15.13	939.06	34.50
	Huan county	879.06	9.52	1774.73	19.22	1169.15	12.66
Middle-extent erosion	Guyuan county	366.95	10.19	239.64	6.65	391.55	10.87
	Fengzhen city	231.61	8.51	218.13	8.01	210.55	7.74
	Huan county	1578.40	17.09	2196.68	23.78	1543.24	16.71
Intensive erosion	Guyuan county	126.24	3.51	63.12	1.75	114.47	3.18
	Fengzhen city	128.02	4.70	107.80	3.96	112.86	4.15
	Huan county	2102.91	22.77	652.46	7.06	2207.42	23.90
More intensive erosion	Guyuan county	40.65	1.13	22.47	0.62	40.65	1.13
	Fengzhen city	38.74	1.42	57.27	2.10	47.16	1.73
	Huan county	3949.91	42.77	2099.98	22.74	2433.05	26.34
Severe erosion	Guyuan county	9.63	0.27	4.28	0.12	13.91	0.39
	Fengzhen city	12.63	0.46	13.48	0.50	21.90	0.80
	Huan county	403.39	4.37	133.81	1.45	257.86	2.79

From a spatial distribution perspective, the transfer of soil erosion levels across the counties reveals a pattern characterized by 'overall stability with localized variations'. In Guyuan County, the pattern of soil erosion predominantly follows a linear trajectory, mirroring the elongated ridge topography of the region. The degree of soil erosion shows an increasing trend from north to south; considering the relatively high vegetation cover index in the southern region and its pronounced topographical undulations, it can be inferred that slope length and gradient factors are significant contributors to soil erosion in this area. In Fengzhen City, soils experiencing slight to moderate erosion are primarily located in the western and central portions of the region, while the eastern area demonstrates more severe erosion, likely attributable to its higher elevation and the susceptibility of mountain soils to erosion and landslides. The spatial distribution of soil erosion in Huan County is characterized by a stepped pattern, with the erosion intensity gradually diminishing from the north to south. Severe erosion areas are concentrated in the northern region of Huan County, where low vegetation cover index and frequent exposure to significant wind and sand damage render it a focal point for desertification control efforts. Due to its location in the loess hilly and gully region, over 90% of the area is covered by loess, resulting in a landscape marked by intersecting gullies and undulating hills. Consequently, the overall degree of soil erosion in this region is comparatively more pronounced than that of the other two study areas (Figure 11).

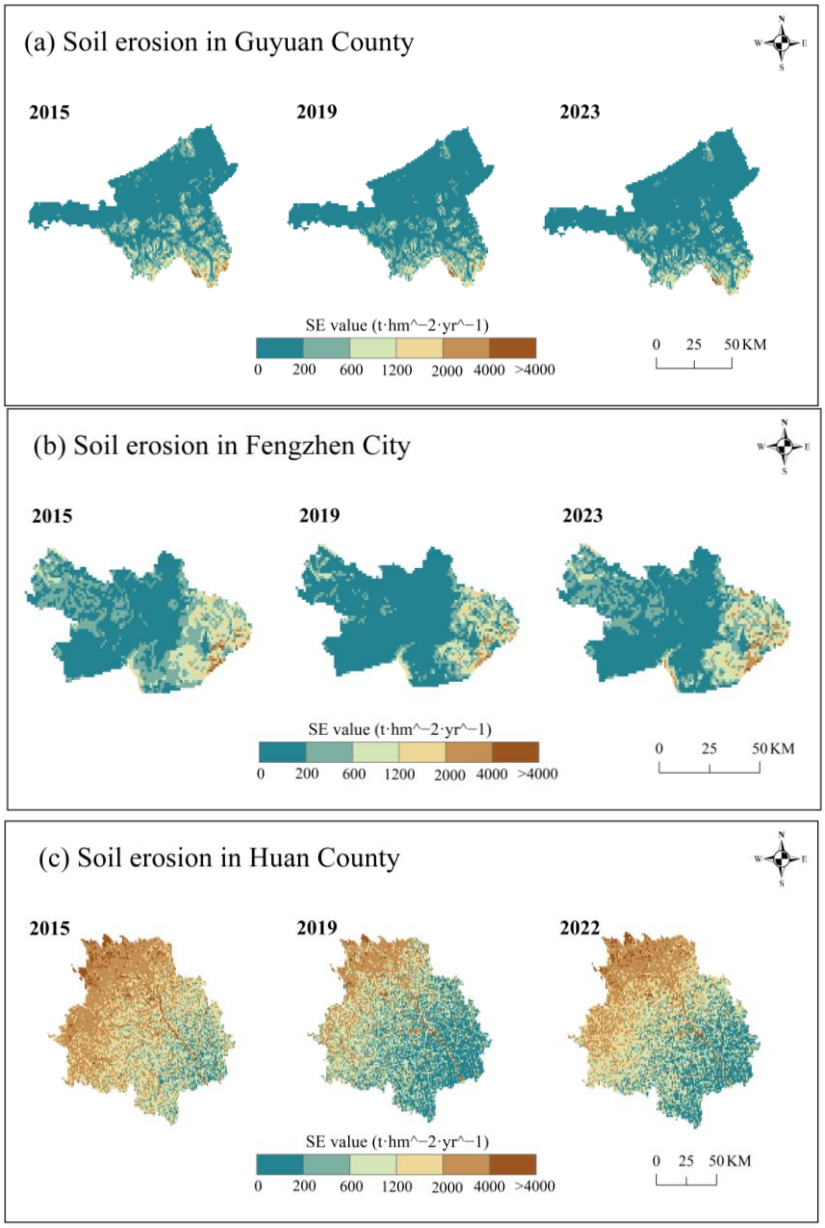

Figure 11. Temporal and spatial changes of soil erosion in fallow counties during 2015–2023.

3.3.6. Ecological Index of Fallow Counties

Under the combined influence of the four environmental quality factors, the Ecological Index in all counties during the implementation of the fallow policy in 2019 was generally higher, indicating that the environmental quality across all counties was better in 2019 compared to other years. Among these, the Ecological Index in Huan County exhibited considerable variability from 2015 to 2019, with an absolute change value of $5 \leq |\Delta EI| \leq 10$. The Ecological Index of Guyuan County and Fengzhen City increased little from 2015 to 2019, and the absolute change value was $2 \leq |\Delta EI| \leq 3$. It follows that the implementation of the fallow policy had a more pronounced impact on the environmental status of Huan County compared to the other two counties. From 2019 to 2023, the ecological environment status of the three fallow counties declined; However, the absolute change value of the Ecological Index in Guyuan County and Fengzhen County was less than 2, indicating a small change range. Influenced by the second round of the fallow policy, the marginal environmental benefits associated with fallowing are trending downward. Nevertheless, the deterioration of the Ecological Index in Huan County was comparatively smaller than that in the other two counties (Table 9).

Table 9. Change rate of ecological index in fallow counties from 2015 to 2023.

Year	Guyuan County	Rate of Change	Fengzhen City	Rate of Change	Huan County	Rate of Change
2015	43.48	\	43.45	\	33.08	\
2019	46.04	5.89%	46	5.87%	38.44	16.20%
2023	45.02	−2.22%	44.63	−2.98%	36.45	−5.18%

4. Discussion

4.1. Layout of Fallow Areas

The layout of fallow land is determined based on the health status of cultivated land and the surrounding ecological environment, reflecting the purpose and significance of fallowing. In recent years, numerous experts have conducted extensive research on the evaluation of fallow land layouts, employing methods such as remote sensing technology and field investigations to ascertain the distribution of fallow plots. Remote sensing monitoring is effective for assessing large areas; however, it faces challenges in predicting the future distribution of fallow areas due to weather variability [42]. Conversely, while field investigations offer high accuracy, they require substantial material resources and manpower, limiting their applicability for large-scale evaluations. Therefore, establishing a scientific assessment system for cultivated land ecological vulnerability can facilitate not only accurate evaluations of the current and historical cultivated land ecological vulnerability but also predictions of future changes in fallow land layout.

The fallow area is predominantly located in the northern and central regions of the northern agro-pastoral ecotone. Owing to the distribution of natural factors such as climatic conditions and soil types, the northern region exhibits a high potential for wind erosion, with a drought frequency exceeding 30% [43]. As a crucial ecological barrier area in China, the central region of the northern agro-pastoral ecotone lies within the ecological stress zone of forest, grassland, and desert, characterized by high sensitivity and fragility. Consequently, the selection of fallow methods should prioritize local conditions, ensuring not only a suitable rest period for cultivated land but also providing high-quality management and protection during this period. This approach aims to gradually improve and restore the utilization conditions of degraded cultivated land, safeguarding the ecological security of cultivated land.

4.2. Discussion on the Implementation of Ecological Effects of Fallow in the Northern Farming-Pastoral Ecotone

Research on the ecological effects of fallow policies remains limited, prompting scholars to draw comparisons with ecological restoration projects. While scholars have evaluated the degree of ecological enhancement from these restoration initiatives by calculating the value of ecosystem services, such assessments do not directly reflect the impact of ecological restoration on soil erosion, particularly in arid and semi-arid regions characterized by significant soil loss. Therefore, this study selected three typical pilot counties from different topographic regions within the northern agro-pastoral ecotone to investigate the ecological effects of fallowing at various time points. Additionally, the study examined the extraction of regional environmental factors using remote sensing data to evaluate the ecological environment status following the implementation of fallow practices. In contrast to the Remote Sensing Ecological Index (RSEI), which is commonly employed to assess ecological quality, the Ecological Index utilized in this study incorporates the biological abundance index, thereby enhancing the measurement of biodiversity and biological resources [44].

4.3. Effect of Fallow Period Length on Ecological Outcomes

The implementation of fallow ecological projects has significantly enhanced ecological land quality and improved the ecological carrying capacity of the land. A comparative analysis of the ecological effects of fallowing in counties with varying fallow durations reveals that counties undergoing a second fallow period exhibit greater ecosystem stability.

Following the conclusion of the fallow pilot project, it is imperative to continue monitoring the ecological benefits associated with land use patterns in the region. For instance, ongoing vegetation restoration efforts in the hilly and gully areas of the Loess Plateau have led to increased agricultural water demand and substantial financial investments in the management of artificial vegetation [41]. This may, in turn, adversely affect the ecological vulnerability of arable land. Once established, vegetation's absorption of groundwater can result in lowered water tables and surface soil desiccation, ultimately causing the death of shallow-rooted plants in adjacent areas [45]. Consequently, the ecological benefits derived from fallow practices may be significantly diminished. Therefore, subsequent ecological planning and management are essential. It is crucial to regulate agricultural water usage within reasonable limits and to strategically plan the utilization of arable land, grassland, and forest land while also protecting and restoring ecosystems such as water bodies, wetlands, and lakes. Additionally, the determination of the specific fallow period should consider the food security pressures within the region [46]. Based on these findings, this paper presents the following recommendations: Future policies from various levels of the Chinese government should optimize spatial configurations for fallowing based on regional differences, thereby formulating appropriate fallow strategies to ensure the restoration of arable land ecosystems; In arid and semi-arid regions, such as Huan county, large-scale afforestation following the conclusion of the fallow period may lead to reduced vegetation cover index and negatively impact ecosystem value; therefore, Therefore, the expansion of ecological land should be carried out slowly; Efforts should be directed towards leveraging the sustained ecological benefits following the fallow period to protect ecosystems such as wetlands and lakes.

5. Conclusions

This study predicted the fallow ecological effects of the fallow areas and typical counties in the northern agro-pastoral ecotone during 2015–2023. The results indicate:

(1) Between 2015 and 2023, the fallow area was primarily concentrated in the desertification degradation area along the Great Wall, particularly in the northern part of the region, where fallow plots exhibited clustering patterns. By 2023, the ecological vulnerability index of cultivated land in these desertified and degraded areas is projected to fluctuate between 0.4 and 0.64. Since 2017, the overall fallow pattern in the region has remained relatively stable, with priority and secondary priority fallow areas predominantly located in the northern and central regions, encompassing approximately 33.46×10^4 km^2.

(2) The bioabundance index in Guyuan County and Fengzhen City initially increased but later decreased during 2015–2023, whereas Huan County exhibited a consistent upward trend, resulting in a higher overall index. This divergence is closely related to the proportion of ecological land use in each county. Specifically, the proportion of grassland in Huan County remained above 80%, while the grassland area in Guyuan County and Fengzhen City showed a downward trend. Conversely, the forest area in these two counties increased, leading to minimal changes in their biological abundance index.

(3) The water network density index in Guyuan County, situated within the Beijing–Tianjin–Hebei water conservation area, was higher than that of other counties and exhibited a gradual upward trend. In contrast, both Fengzhen City and Huan County

experienced slight declines in their water network density indices after 2019. Notably, Huan County, located in the loess hilly gully area, faces significant evaporation and poor hydrological conditions, which contribute to its relatively low overall water network density index.

(4) Guyuan County consistently maintained a high vegetation cover index; low-value areas are mainly distributed in the west. Fengzhen City experienced a substantial increase in the vegetation cover index from 2015 to 2019, stabilizing thereafter. In contrast, Huan County, which is characterized by a relatively low overall vegetation cover index, exhibited high-value areas predominantly in the southern and south-eastern regions, while low-value areas were concentrated in the north. Despite an expansion of forest land, Huan County displayed an overall declining trajectory in the vegetation cover index, particularly from 2019 to 2023. Overall, Huan County experienced a more pronounced decline in the vegetation cover index compared to the other counties during the 2019 to 2023 period.

(5) The soil conservation index of the three fallow counties showed a trend of first increasing and then decreasing. Following the implementation of the fallow project, the dynamics of soil erosion in the fallow counties exhibited a generally positive trend. Guyuan County experienced the most rapid increase in areas of slight erosion, alongside a significant decrease in areas of moderate erosion from 2015 to 2019. In contrast, from 2019 to 2023, Huan County demonstrated a notable transition from high to low erosion areas, reflecting an overall reduction in soil erosion levels. Meanwhile, Fengzhen City displayed considerable temporal variability in the extent of erosion.

(6) The Ecological Index was generally higher across all counties during the fallow policy implementation, indicating improved environmental quality. Huan County showed significant variability ($5 \leq |\Delta EI| \leq 10$) from 2015 to 2019, compared to minimal changes ($2 \leq |\Delta EI| \leq 3$) in Guyuan County and Fengzhen City, suggesting a more pronounced impact of the fallow policy on Huan county. From 2019 to 2023, ecological status declined in all three counties, with minor changes in Guyuan County and Fengzhen City. The results show that the overall environmental quality in 2019 was superior to that in both 2015 and 2023, suggesting that the ecological effects of fallowing exhibit a degree of continuity.

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