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Multi-Perspective Analysis of Land Changes in the Transitional Zone between the Mu Us Desert and the Loess Plateau in China from 2000 to 2020

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Abstract: The transition zone between the Mu Us Sandy Land and the Loess Plateau is considered an ecologically fragile area. However, significant changes in land use have occurred in the past few decades due to changes in land policies and the implementation of major national ecological projects. Despite this, there is still a lack of clear investigation into the impact of these changes on the landscape structure and ecological health of the area. This study utilizes high-resolution annual land use data from China, along with multi-index models and algorithms, to comprehensively analyze regional land use changes, landscape patterns, and the ecological environment's quality. Through a comprehensive analysis of various factors, including changes in quantity, transformation in land types, spatial dynamics, landscape structure, and ecological quality, we aim to provide a better understanding of the complex interactions between land use and ecological systems in this area. The research results indicate that: (1) Since 2000, 9057.4 km^2 of land in the study area has undergone changes. The grassland area has the largest increase, the forest area has the fastest growth rate, while cropland and barren land have decreased to varying degrees, and impervious surface has slightly expanded. (2) The movement trajectory of the center of gravity for different land types is closely related to human activities such as land development and utilization, as well as ecological restoration. Land changes have resulted in an escalation of landscape fragmentation, a reduction in landscape diversity, and a decline in the uniform distribution of different types. (3) Ecological land is the key to improving the ecological environment. The increase in ecological land area in the study area has led to an improvement in the quality of the ecological environment. The net contribution rate of land change to ecological improvement reaches 1.99%. The analysis methods and perspectives used in this study can be applied to other similar studies. The study's findings enhance the understanding of how land and vegetation changes affect the ecological environment in this crucial area. They are of great significance in guiding the development and utilization of land resources and the implementation of ecological environment projects.

Keywords: land change; landscape structure; spatial dynamics; ecological quality; transitional zone

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1. Introduction

For a long time, the transitional zone between the Mu Us sandy land and the Loess Plateau has attracted widespread attention both domestically and internationally due to its fragile ecology and severe soil erosion. With the implementation of a series of ecological management and restoration projects, such as the Three-North Shelter Forest Program (TNSFP) [1], the Grain to Green Program (GTGP) [2], and the National Fiberisation and Connectivity Plan (NFCP) [3], the vegetation coverage has significantly increased, and the ecological environment has gradually improved. However, there is still a lack of detailed research and in-depth understanding of the land type changes and their ecological environmental effects in this area.

As is well known, the spatiotemporal pattern and dynamic characteristics are fundamental areas of research for land change. Most existing studies have analyzed them from the perspectives of quantity change, spatial patterns, intensity, and spatiotemporal dynamics [4–6]. Their advantages lie in precise spatial positioning and distribution, and in determining the total amount and differences in land change. Scholars use modeling methods to analyze the rate, magnitude, regional differences, and characteristic changes in land change in order to gain an in-depth understanding of its processes and trends [7–9]. Commonly used methods include the Markov transfer matrix, dynamic degree model, change rate index, Moran's index, and cellular automaton. Land change objectively documents the changes in the spatial pattern on the Earth's surface. However, it is the land type that serves as the fundamental element of the landscape. Consequently, any land change will unavoidably cause changes in the landscape pattern [10]. Researchers are integrating land data with landscape indicators, such as landscape diversity, dominance, and evenness, to better understand the potential regularity of the landscape patch mosaic. These indicators reflect the landscape characteristics, structural composition, and spatial allocation of land and are widely used to explore land change and landscape structural characteristics [11–13]. In addition, changes in land use are closely linked to ecosystem services through the interactions between humans and the environment [14]. Different types of land have distinct ecosystem service functions, and changes in land use can alter these functions and structures, thereby causing modifications to the ecological environment [15]. The quantification of ecosystem services has always been of great interest, and scholars have conducted extensive research on methods, types of services, and the application of results. Costanza et al. [16] proposed an evaluation method and value coefficient for the global ecological service value, and they were the first ones to realize the quantitative calculation of ecological service value. Xie et al. [17] improved the method based on the characteristics of China's ecological environment and proposed a more practical ecosystem service value per unit of the land area. This method is applicable to different ecosystems in China and has been widely used by Chinese scholars [18–21]. It is worth noting that the degree of land change varies with time and geographical location, and the spatial pattern is the result of changes in land availability, quality, and suitability. At the same time, the impact of land change on ecosystem services also varies with time and space. To fully understand the process of land change and enhance our understanding of its ecological effects, it is necessary to clarify the rate and spatial pattern of land use changes through model analysis. Additionally, we need to analyze the impact and effects of these changes on the environment.

Throughout the existing research, there are several limitations, which is evident from the fact that most studies focus on changes in quantity and spatiotemporal patterns, as well as simulation of changes. Some focus on ecological effects caused by land change, while others focus on spatiotemporal dynamic changes in landscape and changes in structure [22,23]. Despite the existing studies on this topic, a comprehensive and systematic exploration of this topic remains lacking. Especially for the typical fragile region of the transition zone between the Mu Us Sandy Land and the Loess Plateau, where land change is closely related to the landscape pattern and ecological environment, it is of great significance to quantitatively describe and dynamically monitor the impact of the land change pattern, structural characteristics, and ecological environment effects on land resources in this area. This is essential for the rational allocation, development, and utilization of land, effective control of the transformation of land types, ensuring the orderly development of the economy and society, and guiding the construction of the ecological environment.

Therefore, this study aims to analyze land changes in this specific region by utilizing multiple indicators and model algorithms. The analysis will focus on different perspectives, such as quantity, type, space, structure, and quality, in order to address the gaps in existing research and gain a comprehensive understanding of their impact on landscape structure and ecological environment quality. Specifically, this study attempts to answer the following questions:

(1) What changes have occurred in land type in the transition zone between the Mu Us Sandy Land and the Loess Plateau in China since 2000?
(2) How have these land changes affected the spatial structure of the landscape in the region?
(3) What specific ecological impacts have resulted from the changes in land type and landscape structure in the region?

2. Materials and Methods

2.1. Study Area and Data

The transitional zone between the Mu Us Sandy Land and the Loess Plateau is the ecotone where the forest transect and the grassland transect meet in the north and south of eastern China. It is also the transitional zone from the desert steppe to the steppe and further to the forest steppe region, and from the semi-humid climate zone to the semi-arid and arid climate zone [24–26]. The research area, which covers Yuyang District, Hengshan District, Fugu County, Jingbian County, Dingbian County, Mizhi County, Shenmu County, Shenmu City, and 121 administrative townships (streets), is located between 36.10°–39.87° N and 106.83°–112.17° E, with an area of approximately 36,800 km^2 (Figure 1). The study area's altitude ranges from 669 m to 1912 m, with higher terrain in the southwest and lower terrain in the northeast. The soil and geomorphology of the area show an interlaced distribution of sandy dunes, low plateaus, and loess hills. The climate transitions from a semi-arid to semi-humid zone, with an average annual rainfall ranging from 322 mm to 499 mm. The vegetation transitions from desert grassland sandy vegetation to shrubs, cultivated land, and sparse woodland.

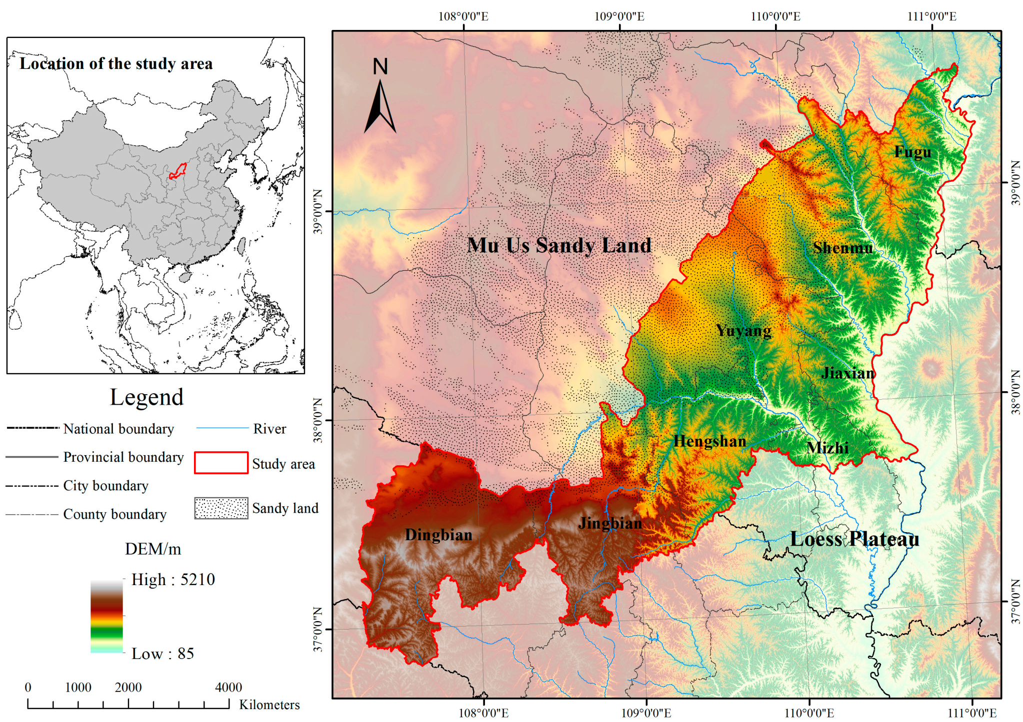


Figure 1. Overview map of the location of the study area.

Land use and land cover data serve as the foundation for this study. The study utilizes the CLCD dataset (Landsat-derived annual China land cover dataset) developed by Wuhan University, which reveals China's land use status with a spatial resolution of 30 m. This dataset describes the land surface with nine land-use and land-cover (LULC) categories.

The research area includes cropland, forest, grassland, water, barren land, and impervious surfaces, comprising a total of six land types. For more information about the CLCD development process, precision inspection, and comparison, as well as typical application cases, please refer to the research conducted by Yang and Huang [27].

2.2. Methodology

The study utilized a multi-indicator model and algorithm to comprehensively evaluate and analyze land changes in the transition zone between the Mu Us Sandy Land and the Loess Plateau. The analysis included the quantity, spatial dynamics, landscape structure, and ecological quality of land changes, and the methods used are presented in Figure 2.

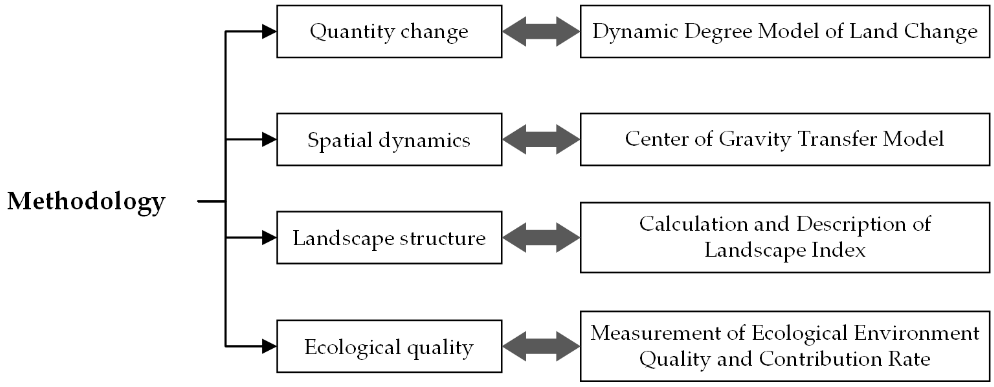


Figure 2. Overview map of the methodology in this study.

2.2.1. Dynamic Degree Model of Land Change

The dynamic degree of land change refers to the quantity change in land types during a certain period, which mainly reflects the intensity and rate of land changes [7,28]. It considers the spatial conversion characteristics between different land types and effectively reflects regional differences in land change. The calculation is as follows:

$$L = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\% \quad (1)$$

In the formula, L represents the dynamic degree of land change, U_a and U_b represent the total area of a certain land type at the start time a and end time b, respectively, and T represents the research time period.

2.2.2. Center of Gravity Transfer Model

The spatial evolution process of land types can be well described through the gravity center migration model, which is evolved according to the common population distribution gravity center principle in population geography [29]. The gravity center coordinates are usually expressed in latitude and longitude and can be calculated using the following method:

$$X_t = \sum_{i=1}^{n} (C_{ti} \times X_i) / \sum_{i=1}^{n} C_{ti} \quad (2)$$

$$Y_t = \sum_{i=1}^{n} (C_{ti} \times Y_i) / \sum_{i=1}^{n} C_{ti} \quad (3)$$

In the formula, X_t and Y_t represent the latitude and longitude coordinates of the barycenter of the land type in year t, respectively. C_{ti} represents the area of the land type in the i-th region, and X_i and Y_i represent the latitude and longitude coordinates of the geometric center of the i-th region, respectively.

The center of gravity migration distance refers to the straight-line distance between the gravity center in a certain year and the gravity center in subsequent years. It can be expressed as follows:

$$L = \sqrt{(X_{t+1} - X_t)^2 + (Y_{t+1} - Y_t)^2} \quad (4)$$

2.2.3. Calculation and Description of Landscape Index

The landscape index quantifies the structural composition and spatial configuration of the landscape pattern. The differences in the type, shape, size, quantity, and spatial combination of landscape patches not only reflect the differences in the quality of landscape functions but also affect the ecological processes of the entire region [30,31].

This study completed the calculation of the landscape index with the help of FRAGSTATS 4.2 software. This study selected four indices based on the types of landscape metrics and their applicability in landscape analysis, at both the class level and the landscape level [32]. At the class level, the indicators selected were: mean patch size (MPS), percentage of patch area (PLAND), number of patches (NP), and patch density (PD). At the landscape level, the selected indicators were: contagion index (CONTAG), landscape shape index (LSI), Shannon's diversity index (SHDI), and Shannon's evenness index (SHEI). The calculation formula and description for the landscape index are presented in Table 1.

Table 1. The calculation formula and description of the landscape index in this study.

Landscape Indicators	Formula	Description
Number of patches (NP)	$NP = n_i$ n_i is the number of patches in the landscape of patch type (class) *i*.	Number of patches of a particular patch type is a simple measure of the extent of subdivision or fragmentation of the patch type.
Patch density (PD)	$PD = N/A$ *N* is the number of all patches; *A* is the landscape area (m^2).	Reflects the degree of fragmentation of the landscape and the degree of spatial heterogeneity of the landscape. To a certain extent, it reflects the degree of human interference in the landscape. The larger the PD is, the higher the degree of fragmentation and the greater the degree of spatial heterogeneity are.
Percentage of landscape (PLAND)	$PLAND = \sum_{j=1}^{n} a_{ij}/A \times 100$ a_{ij} is the area (m^2) of patch *ij*; *A* is the total landscape area (m^2).	Percentage of landscape quantifies the proportional abundance of each patch type in the landscape. Like total class area, it is a measure of landscape composition important.
Mean patch size (MPS)	$MPS = \sum_{j=1}^{n} a_{ij}/n_i$ a_{ij} is the area of patch *ij* (m^2); n_i is the number of patches.	Mean patch size represents the average size of a certain type of patch, which can reflect the degree of fragmentation of the landscape.
Landscape shape index (LSI)	$LSI = \frac{0.25E}{\sqrt{A}}$ *E* is the total length of the edge in the landscape (m); *A* is the landscape area (m^2).	Reflects the complexity of the shape of the overall landscape. The closer the LSI is to 1, the simpler the overall landscape shape is. That is, rules or approximate squares; the larger the LSI is, the more complicated it is.
Contagion (CONTAG)	$CONTAG = 1 + \sum_{i=1}^{m}\sum_{k=1}^{m}\left[P_i \frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}}\right]\left[\ln\left(P_i \frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}}\right)\right]/2\ln(m)$ P_i is the proportion of the landscape occupied by patch type (class) *i*; g_{ik} is the number of adjacencies (joins) between pixels of patch types (classes) *i* and *k* based on the double-count method; m is the number of patch types (classes) present in the landscape, including the landscape border if present.	Reflects the degree of aggregation and extension of different patch types in the landscape; a high contagion value indicates that a certain dominant component in the landscape forms a good connectivity.
Shannon's diversity index (SHDI)	$SHDI = -\sum_{i=1}^{m}(P_i \ln P_i)$ P_i is the proportion of the landscape occupied by patch type (class) *i*.	Reflects the number of landscape components that make up the landscape and the proportion of each landscape component. The greater the value is, the higher the diversity is.
Shannon's evenness index (SHEI)	$SHEI = -\sum_{i=1}^{m}(P_i \ln P_i)/\ln(m)$ P_i is the proportion of the landscape occupied by patch type (class) *i*.	Reflects the uniformity of the distribution of different landscape components in the landscape, and it is an important aspect of the diversity index.

2.2.4. Measurement of Ecological Environment Quality and Contribution Rate

The ecological environment quality index quantitatively characterizes the overall status of the ecological environment quality in a region by comprehensively considering the ecological quality and area ratio of each land type in the region [33]. The calculation formula is:

$$EV_t = \sum_{i=1}^{n} LU_A \times EV_i / TA \tag{5}$$

In the formula, EV_t represents the regional eco-environmental quality index in period t; LU_A and EV_i represent the area and eco-environmental quality coefficient of type i land in the region during period t, respectively; and TA represents the total land area.

By referencing the research results of both domestic and foreign experts and scholars [33,34], and considering the ecological value of various land types in the study area, the ecological environment quality coefficients were determined for each type of land (Table 2). Using Formula (5), the ecological environment quality index can be comprehensively calculated to evaluate the ecological environment quality in the region.

Table 2. Eco-environmental quality coefficients corresponding to different land types.

Land Type	Cropland	Forest	Grassland	Water	Barren Land	Impervious Surfaces
Ecological environment quality coefficient	0.293	0.883	0.798	0.521	0.025	0.175

The contribution rate of the ecological environment refers to the change in regional ecological environment quality caused by the change in a certain land type, and expresses the degree of impact of land changes on the ecological environment in quantitative form [35]. The calculation formula is:

$$LEI = \left(EV_{j,t+1} - EV_{i,t}\right) \times LA/TA \tag{6}$$

In the formula, LEI represents the contribution index of land change to the ecological environment, where $EV_{j,t+1}$ and $EV_{i,t}$ are the ecological environment quality coefficients of land type j at time t+1 and land type i at time t, respectively. LA denotes the area change from land type i to land type j, while TA represents the total area of the region.

3. Results

3.1. Quantity Changes of Land Use

From 2000 to 2020, the land cover in the transition zone between the Mu Us Sandy Land and the Loess Plateau has undergone significant changes. The findings presented in Table 3 indicate that the area of cropland and barren land has decreased notably, by 15.7% (1417.8 km^2) and 92.8% (2340.5 km^2), respectively. In contrast, there has been an increase in the area of grassland, impervious surfaces, forest, and water to varying degrees. Specifically, the areas of grassland, impervious surfaces, forest, and water have increased by 3431.9 km^2, 292.4 km^2, 28.0 km^2, and 6.1 km^2, respectively. Notably, the area of grassland has experienced the most significant increase.

When comparing the periods of 2000 to 2010 and 2010 to 2020, it is evident that the increase in grassland and impervious surfaces was more pronounced in the former period. On the other hand, the increase in forest area was less significant in the 2000–2010 period, indicating an accelerated pace of forest recovery in the most recent ten years. Additionally, there has been a considerable increase in the reduction in cropland in the past decade when compared to the 2000–2010 period, signifying an accelerated pace of farmland retirement. Furthermore, the decrease in barren land over the past ten years has noticeably diminished, indicating a slower rate of ecological recovery. Lastly, there has been a shift in the water area over the last ten years, transitioning from a decrease in the previous decade to an increase.

Table 3. Statistical table of land change area in the study area from 2000 to 2020.

Land Use Type	2000	2010	2020	2000–2010		2010–2020		2000–2020	
				Change Area (km^2)	Proportion of Change Area (%)	Change Area (km^2)	Proportion of Change Area (%)	Change Area (km^2)	Proportion of Change Area (%)
Cropland	9024.1	8867.8	7606.3	−156.3	−1.7	−1261.5	−14.2	−1417.8	−15.7
Forest	2.9	4.8	30.9	1.9	65.5	26.1	543.8	28.0	965.5
Grassland	24,946.9	26,796.9	28,378.8	1850	7.4	1581.9	5.9	3431.9	13.8
Water	139	134.4	145.1	−4.6	−3.3	10.7	8.0	6.1	4.4
Barren land	2521.3	677.1	180.8	−1844.2	−73.1	−496.3	−73.3	−2340.5	−92.8
Impervious surfaces	197	350.2	489.4	153.2	77.8	139.2	39.7	292.4	148.4

From the perspective of the severity and rate of land change (Figure 3), influenced by national ecological governance and restoration projects, the main characteristics of land changes in the transitional zone between the Mu Us Sandy Land and the Loess Plateau were a significant increase in forests and grasslands, varying degrees of reduction in cropland and barren land, and slight expansion of impervious surfaces.

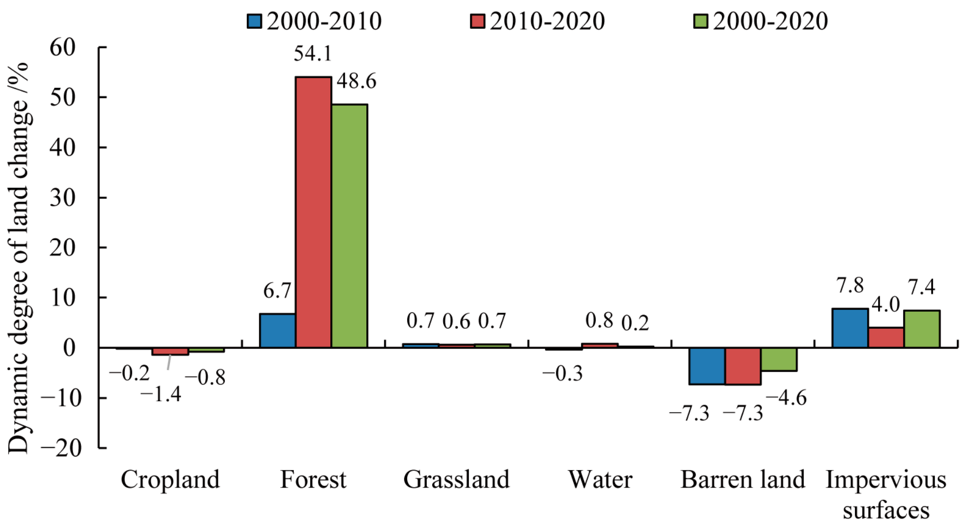


Figure 3. Dynamic degree map of area changes in different land types in the study area.

Among all land types, the most significant dynamic change occurred in forest. The average degree of dynamic change from 2000 to 2020 was 48.6%. The rapid growth of its area mainly occurred in the following 10 years, and the growth rate was about nine times that of the previous 10 years. The growth dynamics of impervious surfaces in different periods were slightly different. After 2010, the expansion rate of impervious surfaces slowed down, with an average annual dynamic change of 7.4%. The area of grassland increased the most, but its dynamic change degree and rate were small. The main reason was that the area of grassland in the study area was large, and the increase in the large area was relatively slight compared to the overall change. The areas of cropland and barren land decreased to different degrees, and the degree and rate of reduction in barren land were significantly higher than that of cropland. The rate of change in the two stages was basically the same, indicating that the barren land was maintaining sustainable and stable ecological recovery. Meanwhile, the decrease in cropland in the past 10 years was significantly higher than that in the previous 10 years. The intensity of returning farmland in the region has increased.

3.2. Land Type Conversion Relationship

From the conversion relationships of different land types (Figure 4), the most significant changes in the study area occur through the mutual conversion between cropland, grassland, and barren land. Grassland experienced the largest change, with a total area of 8736.1 km^2, followed by cropland with 6456.6 km^2, and barren land with a change of 2495.3 km^2. The most significant conversion behavior is the transformation of cropland and barren land into grassland, and some grassland into cropland. A total of 88.6% of barren land has been converted into grassland, 42.6% of cropland resources have been converted into grassland, and 9.5% of low-coverage grassland has been reclaimed as cropland.

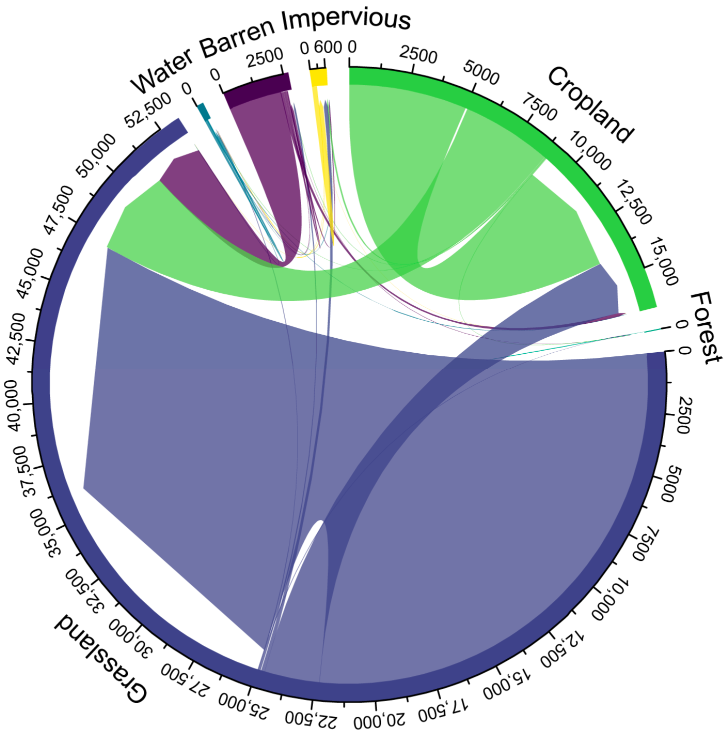


Figure 4. The chord diagram depicting land use changes in the study area between 2000 and 2020.

3.3. Spatial Pattern Dynamics of Land Use

Further exploration of the spatial dynamics of land changes is necessary. Between 2000 and 2020, a total of 9057.4 km^2 of land in the study area experienced changes, which accounted for 24.6% of the total area. The main reasons for these changes included the reduction in a large amount of barren land, dynamic changes in grassland and cropland in the eastern region, an increase in the number of large patches, an improvement in their concentration and connectivity, and a significant expansion of impervious surfaces around urban areas in the northern region (Figure 5).

Figure 6 shows the spatial evolution of the center of gravity of different land types. The overall center of gravity of cropland has a moving trajectory characteristic from southwest to northeast. Between 2000 and 2017, the area of cropland reclamation in the southwest increased while the area of cropland on steep slopes in the northeast decreased, resulting in a main movement of cropland towards the southwest of about 19.3 km. After 2017, some barren land in the northeast region was converted into cropland due to ecological restoration, causing the center of gravity of the cropland to shift approximately 9.6 km in the northeast direction.

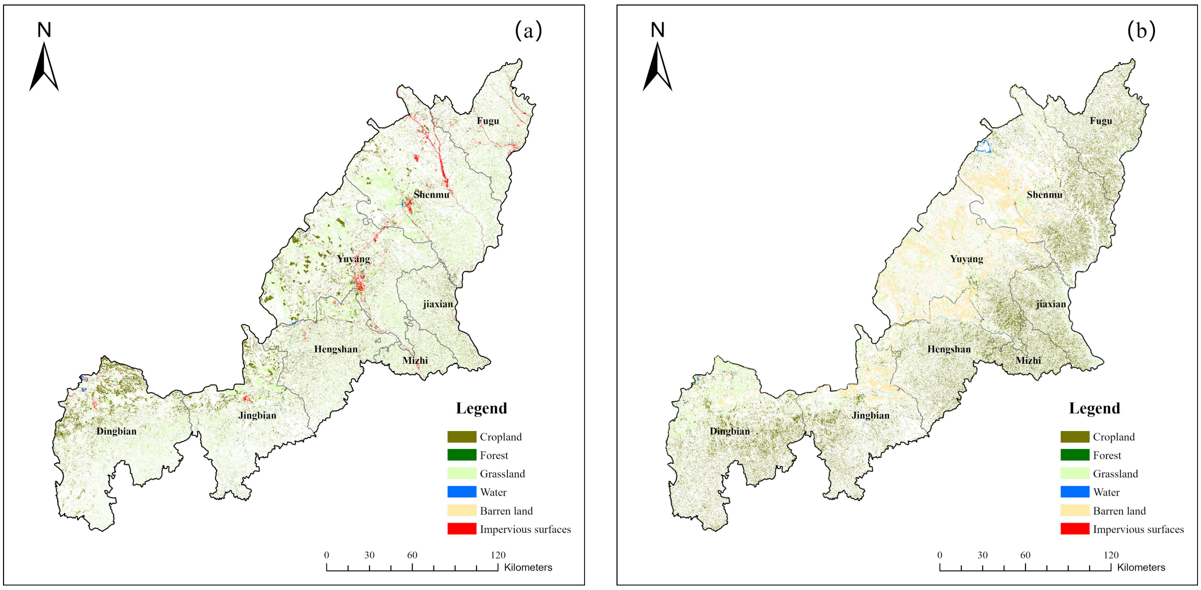


Figure 5. The spatial distribution of land change in the study area from 2000 to 2020. (**a**) There were gains in land cover types in the study area between 2000 and 2020; (**b**) There were losses in land cover types in the study area between 2000 and 2020.

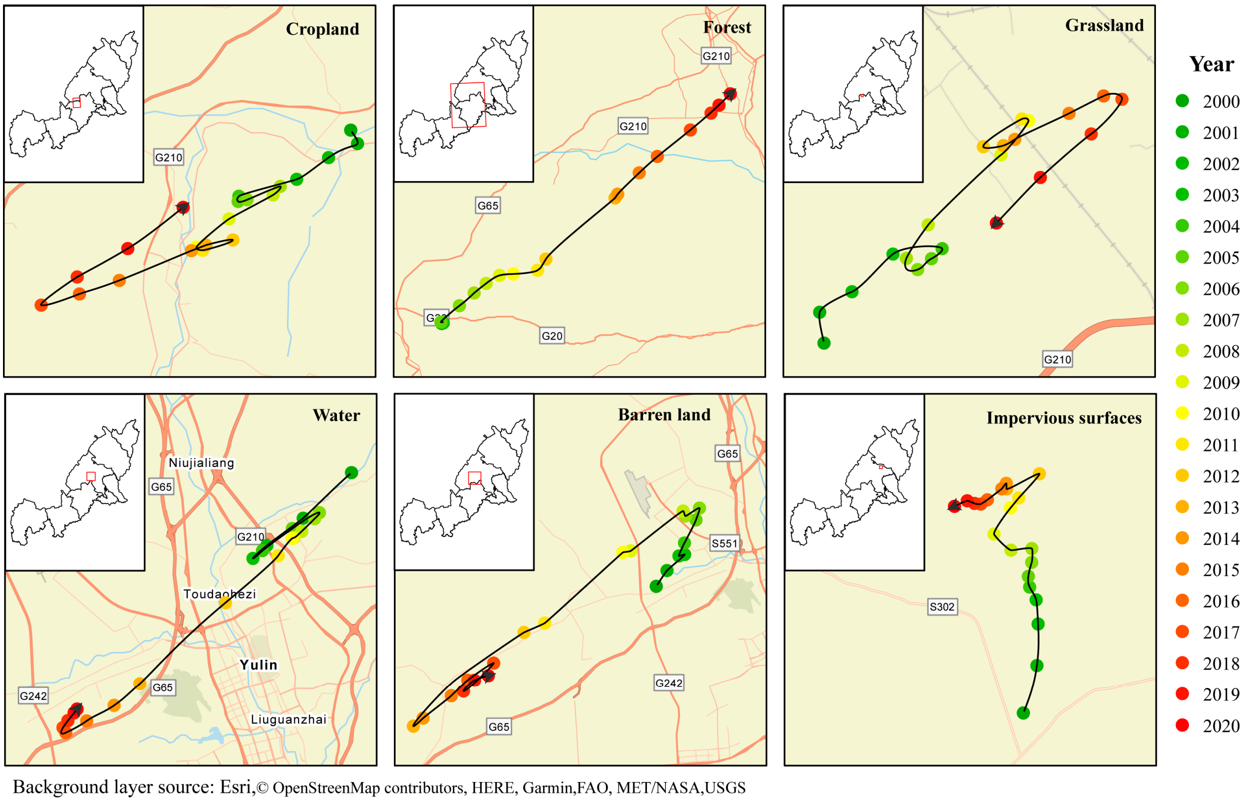


Figure 6. Changes in the center of gravity trajectory of different land use types in the study area from 2000 to 2020.

In contrast to the changes in cropland, the center of gravity of the grassland initially moved towards the northeast direction, but later reversed towards the southwest direction. At the beginning and end of the research period, the center of gravity of the grassland moved approximately 3.2 km. Between 2000 and 2017, returning cropland to grassland caused the center of gravity of the grassland to shift approximately 5.8 km towards the northeast. However, from 2017 to 2020, ecological restoration of sandy barren land in the southwest led to an increase in grassland, causing the center of gravity to shift approximately 2.7 km towards the southwest.

The center of gravity of forest land has been shifting towards the northeast direction, moving approximately 97.4 km. This indicates that the core of afforestation in the study area is located in the northeast direction and is also the primary region for increasing forest.

The center of gravity of the water followed a round-trip path in the northeast and southwest directions from 2001 to 2006, then shifted towards the southwest direction before moving back towards the northeast direction in 2017. In total, the center of gravity of the water moved approximately 21.1 km towards the southwest.

The movement of the center of gravity in the barren land is quite complex. Initially, it shifted towards the northeast, then turned towards the southwest, and finally exhibited slight dynamic movement back and forth between the southwest and northeast directions. This movement is closely linked to the ecological restoration of the barren land in the region, which involves converting it into forests, grasslands, or cropland, as well as a small amount of development into impervious surfaces.

Initially, the center of gravity for impervious surfaces moved northward, following an inverted "S"-shaped trajectory towards the northwest from 2007 to 2020, with an overall movement of approximately 4.7 km in that direction. The regional construction land has continued to expand, and the development intensity of impervious surfaces in the north was considerably higher than that in the south.

3.4. Structural Characteristics of Landscape in Land Change

The landscape index can, to some extent, reflect the spatial configuration characteristics, such as the area and shape of the landscape pattern, as well as the heterogeneity and fragmentation degree of the landscape. This provides a basis for further exploring the relationship between changes in the land's landscape pattern and changes in ecological environmental quality.

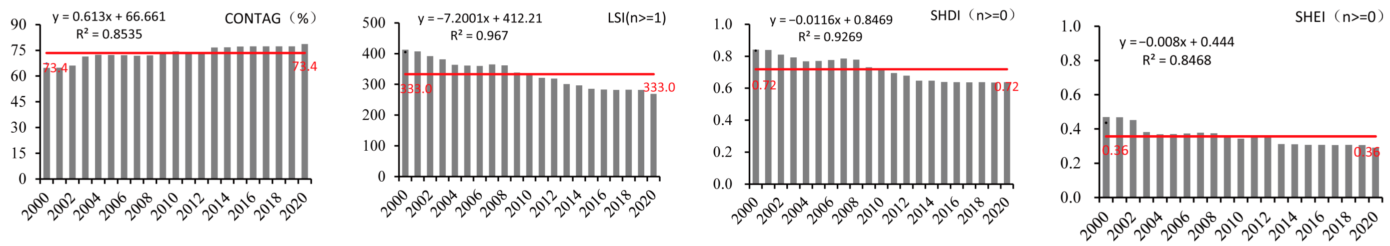
At the class level, the landscape index indicates (Table 4) that grasslands have much larger MPS and a higher PLAND compared to other types, mainly existing in the form of large patches. Cropland has the largest number of patches, and the percentage of patch area in the landscape is second only to grassland, making it one of the main land types in the study area. From 2000 to 2020, although both grassland and forest areas increased, the number and average patch density of forest increased, leading to an increase in fragmentation. In contrast, the NP and PD of grassland decreased year by year, while the MPS increased. This resulted in a decrease in fragmentation, an increase in aggregation, and a relatively concentrated distribution of landscape structural features.

Table 4. The landscape indexes change at the class level between 2000 and 2020.

Land Use Types /Year	MPS (hm^2)		PLAND (%)		NP ($n \geq 1$)		PD (pcs/100 hm^2)	
	2000	2020	2000	2020	2000	2020	2000	2020
Cropland	4.2654	4.1563	24.5013	20.6518	211,563	183,005	5.7441	4.9688
Forest	0.4211	0.6129	0.0078	0.0838	684	5036	0.0186	0.1367
Grassland	30.4071	59.8558	67.7331	77.0511	82,043	47,412	2.2275	1.2873
Water	5.8316	5.7209	0.3773	0.3938	2383	2535	0.0647	0.0688
Barren land	2.7096	0.7287	6.8456	0.4908	93,052	24,809	2.5264	0.6736
Impervious surfaces	0.2919	0.6688	0.5348	1.3286	67,489	73,167	1.8324	1.9865

On the other hand, as construction land continues to expand towards the outskirts of cities and towns, its NP, PD, and MPS have all increased, indicating that not only does the number of impervious surfaces increase, but the area also gradually increases, presenting a "big pie" development model. The number and density of patches in the water slightly increase, while the average patch area decreases, leading to an increase in overall patch fragmentation. Due to the decrease in ecological restoration area, the proportion of patch area to landscape has decreased in barren land. Although the number and density of patches have decreased, the average patch area has also significantly decreased, and the trend of fragmentation has continued to increase.

The landscape index at the landscape level shows, as depicted in Figure 7, that between 2000 and 2020, the CONTAG exhibited an upward trend, indicating an increase in the level of landscape patch aggregation. The LSI reflects the complexity of the overall landscape shape, which exhibited a downward trend, indicating a tendency towards regularization in the shape of landscape patches. The SHDI and SHEI exhibit a consistent decreasing trend over time, indicating a decline in landscape diversity and the evenness of landscape type distribution due to the constant updating and succession of different landscape types. Land use changes disrupt the previous balance in landscape proportion allocation, resulting in a redistribution of the proportion and shape of each landscape type, which in turn leads to a reduction in both landscape diversity and the evenness of landscape type distribution.



(**a**) (**b**) (**c**) (**d**)

Figure 7. The landscape index changes at landscape level from 2000 to 2020. (**a**) The contagion index (CONTAG); (**b**) The landscape shape index (LSI); (**c**) The Shannon's diversity index (SHDI); (**d**) Shannon's evenness index (SHEI). The red line represents the average value of the study area between 2000 and 2020.

3.5. Changes in Ecological Environment Quality

The quality of an ecological environment in a region depends on the value of ecosystem services per unit area provided by different land types and the land use structure. Generally, expanding ecological land such as forests, grasslands, and water has led to a significant improvement in the regional ecological environment. As shown in Figure 8, the ecological environment quality index of the study area has increased by 10.2% from 0.61 in 2000 to 0.68 in 2020. However, there was a slight downward trend observed between 2006 and 2008. This was caused by the reduction in the area of high-quality ecological grasslands due to farmland reclamation, resulting in a decline in their environmental quality. Although the ecological land area slightly decreased in 2008 compared to 2007, the ecological environment quality index increased by 0.001. This was due to the transformation of different land types within the ecological land, where low ecosystem service quality land types became transformed into high-quality ones, enhancing the ecological environment quality. Thus, the slight reduction in ecological land area during that period did not significantly impact the overall ecological environment quality. To sum up, the quality of the ecological environment is closely associated with changes in the ecological land area, with an increase being the primary driver of the improvement in ecological environment quality.

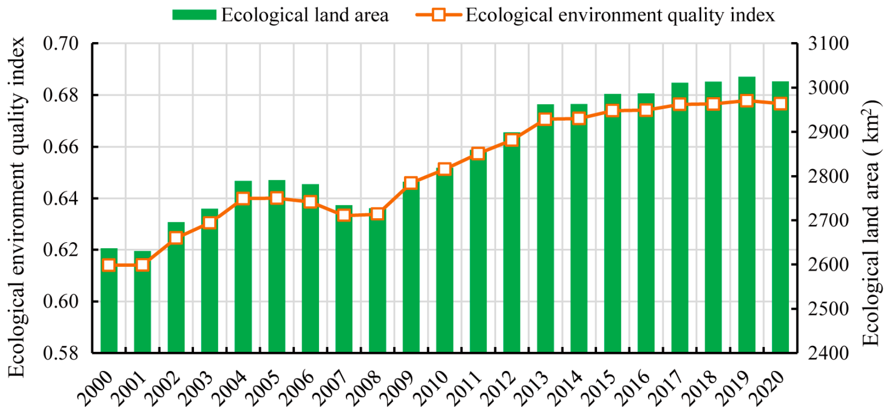


Figure 8. The changes in the quality of the ecological environment in the study area from 2000 to 2020.

3.6. Contribution of Land Changes to Ecological Environment

The quality of the ecological environment in a region is closely related to land-use change. The mutual transformation between land types characterized by low and high ecological environment quality coefficients results in two contrasting trends regarding the improvement and deterioration of ecological environment quality [35]. To reveal the impact of land-use conversion on regional ecological environment quality, we measured the contribution rate of land-use change to the ecological environment (Table 5). The results showed that the restoration of barren land to grassland and the conversion of cropland to grassland were the main drivers behind the enhancement of ecological environment quality, resulting in a determined ecological contribution rate of 5.57%. Conversely, Conversely, the encroachment of cropland and impervious surfaces onto grassland emerged as the primary cause for the deterioration in ecological environment quality, with a determined ecological contribution rate of −3.54%. Due to the rapid development of the economy and the acceleration of industrial and urbanization processes, excessive cultivation of grasslands and the encroachment of urban and rural living areas on grasslands and arable land have largely concealed some ecological effects. However, overall, the ecological benefits of planting grass in wasteland and returning farmland to forests and grasslands are relatively significant, and these measures have helped curb the deterioration of ecological environment quality. The net contribution rate of land-use change to ecological improvement is 1.99%, and the regional ecological environment quality is showing an improving trend.

Table 5. The contribution and impact of land use change on ecological environment quality.

Deterioration of Ecological Environment Quality			Improvement of Ecological Environment Quality		
Change Type	**Change Area (km^2)**	**Contribution Rate (%)**	**Change Type**	**Change Area (km^2)**	**Contribution Rate (%)**
Cropland→Barren land	4.49	0.003	Cropland→Forest	6.30	0.010
Cropland→Impervious surfaces	70.49	0.023	Cropland→Grassland	3841.18	0.886
Forest→Cropland	0.013	0.00002	Cropland→Water	14.71	0.009
Forest→Grassland	0.009	0.000002	Grassland→Forest	21.62	0.005
Forest→Water	0	0	Water→Forest	0.017	0.00002
Forest→Barren land	0	0	Water→Grassland	9.53	0.007
Forest→Impervious surfaces	0	0	Barren land→Cropland	136.71	0.099
Grassland→Cropland	2363.08	3.240	Barren land→Forest	0.087	0.0002
Grassland→Water	21.11	0.016	Barren land→Grassland	2232.90	4.686
Grassland→Barren land	70.34	0.148	Barren land→Water	7.61	0.010
Grassland→Impervious surfaces	175.93	0.298	Barren land→Impervious surfaces	40.60	0.017
Water→Cropland	17.96	0.011	Impervious surfaces→Cropland	1.63	0.0005
Water→Barren land	2.50	0.003	Impervious surfaces→Forest	0	0
Water→Impervious surfaces	12.76	0.012	Impervious surfaces→Grassland	0.378	0.0006
Impervious surfaces→Barren land	0.028	0.00001	Impervious surfaces→Water	5.39	0.005
total	2738.70	3.75	total	6318.66	5.74

4. Discussion

In this study, we used the CLCD dataset, which has better temporal and spatial resolution compared to other datasets such as MCD12Q1, CCI-LC, GlobeLand30, and GLC_FCS30. However, the CLCD dataset still represents a significant source of uncertainty in the dynamic analysis of land change in the study area. The reliability of the analysis results excessively relies on the accuracy of the CLCD dataset. The transition zone between the Mu Us Sandy Land and the Loess Plateau has unique land characteristics, resulting in spectral similarity between cropland and grassland. As a result, there is a possibility of misclassifying land types due to potential Landsat imagery pixel mixture impacts [36]. Regarding the mapping methods used, this dataset considers the continuity of land types between years to ensure the highest possible level of data accuracy. The overall accuracy of land classification is 79.31% [27], which is better than other Landsat-derived land datasets mentioned earlier and is suitable for research and analysis purposes.

This study uses ecological valuation to establish a quantitative relationship between land change and ecological environment quality. While this method has been widely applied [18,37], the comprehensive analysis in this study still lacks exploration of the factors that influence land change and the mechanisms that drive it. Given the size of the research content and the focus on analysis of land change, future studies will explore methods such as principal component analysis and geographic detectors [38–40]. The follow-up study will integrate factors such as natural conditions, social economy, and policies to construct a predictive model that can simulate future changes and provide valuable recommendations for the government's decision making.

In addition, the research results reveal noteworthy changes in the transitional zone between the Mu Us sandy land and the Loess Plateau since 2000. These land changes align more closely with the findings of existing studies, with human activities identified as the primary influencing factor [41,42]. The implementation of policies such as the National Plan to Combat Desertification (2005–2010) and the subsequent National Plan to Combat Desertification (2011–2020) has played a significant role in facilitating these transformations [43,44]. Despite significant changes in the land within the study area, the improvement in ecological environment quality is not substantial. The net contribution rate of land change to the enhancement of ecological environment quality is 1.99%, which is attributed to variations in the ecological effects generated by different land types [45,46]. Therefore, we recommend that, guided by the principles of ecological civilization construction and the latest land space planning, careful attention should be given to the ecological effects of different land types when implementing ecological engineering construction and the policy of converting farmland to forests and grasslands.

5. Conclusions

This study presents a comprehensive analysis of the land changes that have occurred in the Mu Us Sandy Land and the Loess Transition Zone since 2000. The analysis covers various aspects, including quantity change, type transformation, spatial dynamics, landscape structure, and ecological quality. To avoid incomplete understanding, the study employs multiple perspectives in its land change analysis. The research results provide valuable insights into how changes in land and vegetation in this key area affect the ecological environment. The study's results indicate that since 2000, there have been changes in a total of 9057.4 km^2 of land located in the transition zone between the Mu Us Sandy Land and the Loess Plateau. These changes have mainly resulted in the reduction in cropland and barren land to varying degrees, with the largest increase in grassland area and the fastest growth rate in forest area. Among these changes, 88.6% of barren land has been converted into grassland, 42.6% of cropland has been converted into grassland, and 9.5% of low-covered grassland has been reclaimed for cropland. Additionally, 70.0% of the existing forest has resulted from the ecological restoration of low-covered grassland and afforestation, while 20.4% comes from returning farmland to forest. As landscape fragmentation increases due to these land changes, the connectivity within certain advantageous landscape components increases, but the diversity and diversity and uniformity of landscape type distribution decrease. Overall, the area of ecological land has increased, and the quality of the ecological environment has shown an improving trend. The ecological restoration of barren land to grassland and the conversion of cropland to grassland were the main factors that promoted the improvement of the ecological environment quality in the study area.

The methods and perspectives of analysis utilized in this study are applicable to land change research in other areas. The study's findings can serve as scientific references for the rational distribution, development, and utilization of land resources in the transition zone between the Mu Us Sandy Land and the Loess Plateau, as well as guide ecological environment construction.

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