**Article**

**Landscape Dynamics of the Mu Us Sandy Land Based on Multi-Source Remote Sensing Images**

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**Abstract:** This study meticulously investigates landscape alterations within the Mu Us Sandy Land, a critical region for desertification control in China. The research dissects the dynamic characteristics and inter-conversion of landscape elements across eleven distinct periods by employing multi-source remote sensing imagery spanning 1963 to 2020, alongside visual interpretation, random forest classification, and the desertification difference index (DDI). The analysis uncovers significant landscape transformations within the Mu Us Sandy Land over the past six decades, following a precise chronological sequence. A pivotal shift occurred around 1986, characterized by opposing trends within fixed and shifting sandy land. The earlier stage (pre-1986) witnessed a substantial decrease (66.9%) in the fixed sandy land area, accompanied by a corresponding rise (38.7%) in shifting sandy land. Conversely, the later stage (post-1986) era exhibited a remarkable increase (309.7%) in fixed sandy land, alongside a significant decline (78.9%) in shifting sand land coverage. This study identifies two stages of landscape transformation: a pre-1986 phase dominated by the conversion of fixed sandy land to semi-fixed sandy land and a post-1986 reversal toward shifting sand land into fixed sandy land. These sequential transformations have shaped the landscape pattern alterations observed in the Mu Us Sandy Land since 1963. The dramatic landscape improvements observed after 1986 can be primarily attributed to the implementation and continued investment in large-scale ecological restoration projects. This study’s findings, which reveal the intricate landscape dynamics and their implications for ecosystem management, provide a scientific foundation for refining and formulating comprehensive strategies to control desertification and manage the Mu Us Sandy Land’s unique ecosystem.

**Keywords:** Mu Us Sandy Land; multi-source remote sensing images; landscape pattern; transfer matrix

1. Introduction

Human activities have substantially altered terrestrial landscapes worldwide, with land-use and land-cover modifications directly influencing landscape patterns [1–4]. This is particularly significant in arid and semi-arid regions where vegetation distribution and growth are susceptible to climatic factors and human interventions [5,6]. Unsustainable human practices can fragment landscapes, directly impacting energy flows and material cycles within ecosystems [7–10]. Desertification, which is a major ecological concern in these regions, is closely connected to the evolution of landscape patterns. Understanding
changes in landscape patterns is crucial for comprehending the processes and mechanisms of desertification [11–13].

Vegetation cover reduction often leads to soil erosion and desertification, further altering landscape patterns and creating a vicious cycle [14,15]. Conversely, increased vegetation cover can reverse desertification by stabilizing soil, mitigating wind and water erosion, and improving landscape patterns [16–18]. Therefore, studying landscape pattern changes is valuable for comprehending vegetation dynamics and essential for formulating effective desertification control measures.

The Mu Us Sandy Land, a critical ecological security barrier in northern China, has attracted significant research concerning landscape pattern change [19,20]. Implementing ecological restoration projects, such as the Three-North Shelterbelt Development Program and the Grain for Green Program, has improved the ecological environment in recent decades [21,22]. Research suggests these policies have effectively curbed desertification, enhanced vegetation cover, and driven positive landscape pattern changes [23,24].

However, the existing studies mainly focus on specific periods, individual ecological restoration measures [16,25,26], or particular regions within the Mu Us Sandy Land [27,28]. Using multi-source remote sensing images for desertification monitoring allows for the full utilization of remote sensing resources and longer research cycles. This method has been widely used in the field of desertification and landscape change research [29–31]. While previous studies have employed multi-source satellite imagery to analyze landscape pattern changes in the Mu Us Sandy Land, satellite image archive availability limitations have restricted prior analyses to periods commencing in the 1980s or 1990s [32–34]. Consequently, these studies lack a comprehensive understanding of the long-term landscape pattern evolution, particularly during the critical stages of desertification within the Mu Us Sandy Land. Notably, the characteristics of surface vegetation changes and human activities differ significantly between desertification expansion and reversal stages [35,36]. A comprehensive understanding of landscape pattern changes at various stages of desertification evolution is crucial for accurately identifying their driving forces.

This research establishes a landscape classification system utilizing multi-source remote sensing imagery. This system enables the creation of a spatiotemporal database chronicling landscape changes within the Mu Us Sandy Land. By analyzing the conversion relationships between landscape element types and their area variations, this study identifies critical years demarcating significant shifts in the region’s landscape since 1963. Furthermore, this research elucidates the characteristic landscape evolution of the Mu Us Sandy Land across different periods. The analysis explores the natural and human factors that influence the changes in the landscape. These findings provide new insights into the complexities that shape the region’s landscape dynamics. This contributes to developing effective ecological protection strategies and can help create sustainable development management plans.

2. Study Area

The Mu Us Sandy Land, one of China’s four major sandy lands, occupies a transitional zone between the Loess Plateau and the Ordos Plateau, serving as a critical ecological security barrier in northern China. Encompassing approximately 38,000 square kilometers, the Yellow River bounds this region to the east and west, with the Hobq Desert to the north and roughly aligning with the Ming Great Wall to the south. The terrain gradually rises from southeast to northwest, ranging from 900 to 1600 m. A continental semiarid climate characterizes the Mu Us Sandy Land, featuring short, warm summers and long, cold winters. The annual precipitation varies from 250 to 440 mm, decreasing from southeast to northwest. The average annual temperatures range from 6 to 9 °C, with evaporation significantly exceeding precipitation. The region experiences high wind speeds, uneven distribution of surface water resources, and saline–alkaline lakes. Aeolian sandy soil and calcareous soil dominate the soil composition, while the vegetation primarily consists of sandy and meadow communities, with the *Artemisia ordosica* community being
particularly prevalent. Encompassing portions of the Inner Mongolia Autonomous Region, Shaanxi Province, and the Ningxia Hui Autonomous Region, the Mu Us Sandy Land is a significant “agricultural–pastoral transition zone” within China (Figure 1). Notably, animal husbandry and agriculture distribution are transitional, shifting from northwest to southeast.

Figure 1. An overview map of the Mu Us Sandy Land. (a) The location of the Mu Us Sandy Land. (b) The spatial distribution of yearly precipitation. (c) Map of cities, administrative divisions, and river distribution.

3. Methods
3.1. Data Acquisition and Preprocessing

Field surveys were conducted across multiple visits in July 2019, August 2020, and July–September 2022 to understand the on-site composition and characteristics of the Mu Us Sandy Land landscape elements. These surveys focused on various landscape types, including vegetation characteristics, soil properties, and shape features. Additionally, unmanned aerial vehicle (UAV) orthophotos were acquired at a height of 150 m and a range of 1 km × 1 km for typical landscape areas. A total of 326 quadrats (fixed, semi-fixed, and shifting sandy land) were surveyed at 5 m × 5 m, with data collected on plant species abundance and vegetation cover within each quadrant. Furthermore, 141 cultivated land verification points were established on-site. Ultimately, 95 UAV orthophotos were obtained.

Various historical remote sensing image resources were utilized to analyze the spatial distribution and area of the landscape elements across different periods. The landscape interpretation for each period is detailed as follows:
1963: A combination of 1 ARGON image (August 1963, 140 m resolution) and 16 CORONA images (August 1964, 3.6 m resolution) was employed.

1973 and 1978: The interpretation relied on Landsat MSS imagery alongside 23 scenes of CORONA images (March 1971, 3.6 m resolution).

1986–2010: The analysis utilized Landsat TM images (acquired from August to September) combined with WorldView-2 imagery (August 2010, 0.5 m resolution).

2015 and 2020: The interpretation employed Landsat OLI images (acquired from August to September) in conjunction with high-resolution drone imagery (September 2020, 5 cm resolution).

The WorldView images were commercially acquired, while the drone images were captured on-site using a DJI Phantom 4 RTK drone. All other image data were obtained from the United States Geological Survey (USGS) EarthExplorer website: https://earth explorer.usgs.gov/(accessed on 09 03 2022). The meteorological data came from the National Meteorological Administration website: https://data.cma.cn/en/(accessed on 21 10 2022), and the socioeconomic data were sourced from local government statistical yearbooks and bulletins.

The image processing steps were implemented to facilitate a time series analysis of the Mu Us Sandy Landscape. For the ARGON and CORONA images, mosaicking and georeferencing were performed using Google Earth imagery. Subsequently, these images were cropped to the study area boundaries and uniformly converted to the UTM 49N projection for further analysis.

Landsat MSS, TM, and OLI images utilized Landsat Collection 2 Level-2 data provided by USGS. This data source is recognized for its high radiometric and geographic accuracy, making it ideal for surface time series change analysis. Typically, these images do not require additional georeferencing or geometric correction. The pre-processing steps included radiometric calibration (converting the original DN value recorded by the sensor into the reflectivity of the outer surface of the atmosphere, intending to eliminate errors caused by the sensor itself), image mosaicking, and cropping to ensure data consistency.

3.2. Landscape Element Types

Leveraging a combination of field survey data, drone image characteristics, and established research findings, six primary landscape element types were identified within the Mu Us Sandy Land:

1. Fixed Sandy Land: Characterized by vegetation coverage exceeding 30%.
2. Semi-Fixed Sandy Land: Sandy areas with vegetation cover ranging from 10% to 30%.
3. Shifting Sandy Land: Sandy areas exhibiting vegetation coverage below 10%.
4. Cultivated Land: Land primarily dedicated to crop production.
5. Water Area: Encompassing lakes, rivers, reservoirs, and similar features.
6. Residential Area: Including urban and rural settlements and other human habitation zones.

3.3. Landscape Classification Methods

3.3.1. Landscape Classification for ARGON Images (1963)

Given their dominant presence within the Mu Us Sandy Land, the fixed, semi-fixed, and shifting sand land categories were prioritized in the classification process. These categories exhibit distinct brightness gradients within the imagery. Consequently, the classification approach focused on the initial sandy land type differentiation, followed by the interpretation of the remaining landscape elements.

Rationale for Data Selection:

The ARGON images offered suitable spatial coverage of the Mu Us Sandy Land with consistent radiometric properties, making them ideal for landscape classification across the entire region. However, their lower spatial resolution limited their ability to capture more minor landscape features. Conversely, the CORONA images provided superior
spatial resolution, enabling the visual identification of smaller elements like cultivated land, water bodies, and settlements. However, inconsistencies in brightness among the image strips rendered them unsuitable for sand patch classification.

Classification Workflow:
To capitalize on the strengths of both image sources, the following classification workflow was implemented:

Selection of Representative Areas: Six high-quality and representative areas were chosen from the CORONA images, encompassing various landscape types and locations across the Mu Us Sandy Land (Figure 2a,b).

Supervised Classification and Vegetation Cover Assessment: These representative areas were supervised to generate a vegetation classification map. Subsequently, vegetation cover within a 30 m grid was calculated (Figure 2c–e serve as examples).

Random Sampling and Brightness Value Extraction: Five thousand random sampling points, excluding non-sandy locations, were generated within the representative areas. The corresponding brightness values from the ARGON images were then extracted for each sampling point (Figure 2f).

Vegetation Cover-Based Classification and Brightness Interval Calculation: Based on the vegetation cover information at each sampling point, the points were classified into the fixed, semi-fixed, and shifting sand land categories. Brightness interval counts were established for each sand type (Figure 3).

Desertification Type Thresholding and Brightness Segmentation: Desertification-type brightness thresholds were determined, and a brightness segmentation classification method was applied. This process generated a distribution map of the sandy landscape elements for 1963.

Visual Interpretation of Additional Landscape Elements: Cultivated land, water bodies, and residential areas were interpreted visually using the CORONA images.

Merging Classification Results: Finally, the sand classification results obtained from the brightness segmentation were merged with the visually interpreted landscape patches to produce the final Mu Us Sandy Land classification map based on ARGON images.
Figure 2. Sampling steps of desertification lands using CORONA and AGRON images. (a) The typical area selected from the high-resolution CORONA image; (b) the CORONA image of the typical area was supervised and classified to extract the vegetation coverage; (c–e) the original CORONA image of the example area, the vegetation coverage area extracted by the supervised classification, and the vegetation coverage under the 30 m grid level; (f) the 30 m vegetation coverage calculated from the CORONA image of the typical area was randomly sampled, and the AGRON image brightness value corresponding to each sampling plot was calculated and extracted.

Figure 3. Frequency distribution of AGRON image brightness sampling for different desertification lands. The green, blue, and red lines represent the normal curves of fixed, semi-fixed, and shifting sandy land brightness sampling points, respectively.
3.3.2. Landscape Classification for Landsat MSS Images (1973 & 1978)

Building upon the approach used for ARGON images, the classification of landscape elements in the Mu Us Sandy Land for 1973 and 1978 leveraged Landsat MSS imagery. A combined approach addressed the lower spatial resolution of the MSS images compared to the CORONA data. This involved utilizing high-resolution CORONA images for the initial training and reference and the spectral information from the tasseled cap transformation of the Landsat MSS images. The overall classification method and steps remained consistent with the methodology used for ARGON images, with the primary difference being substituting the ARGON image brightness component with the transformed brightness component derived from the Landsat MSS data.

3.3.3. Landscape Classification for Landsat TM/OLI Images (1986–2020)

The landscape classification for 1986–2020 relied on a combination of Landsat TM and OLI multispectral imagery. The extraction of fixed, semi-fixed, and shifting sand land types leveraged the desertification difference index (DDI) in conjunction with high-resolution WorldView imagery and drone orthophotos. Random forest classification was employed for cultivated land extraction, while water bodies and residential areas were classified using index methods.

Desertification Difference Index (DDI) Construction:
The vegetation–soil characteristic spatial model was utilized for desertification assessment since fixed, semi-fixed, and shifting sandy land represent landscape elements and desertification degrees. This involved analyzing the correlation between the vegetation indices and the soil brightness indices to identify the most suitable combination for the Mu Us Sandy Land. The soil brightness index (SBI) and the modified soil-adjusted vegetation index (SAVI) exhibited the strongest correlation for the Landsat TM and OLI images. Consequently, a SAVI-SBI model was established to distinguish varying desertification levels and to construct a DDI model reflecting desertification changes.

The SBI component was derived from the tasseled cap transformation of Landsat images. The SAVI formula is as follows:

$$ SAVI = \frac{NIR - R}{NIR + R + L} \times (1 + L) $$

where $NIR$ represents the near-infrared band, $R$ represents the red band (corresponding to bands B5 and B4 for Landsat 8 OLI and bands B4 and B3 for TM data), and $L$ is the soil adjustment factor, typically set to 0.5 for diverse land cover conditions.

The vertical distribution within the SAVI-SBI feature space reflects the desertification severity [16, 37–38]. Therefore, a binary expression was fitted to differentiate among desertification degrees, enabling the construction of a DDI model:

$$ DDI = a \times V I - S I $$

where $DDI$ represents the desertification difference index, $VI$ represents the vegetation index, $SI$ represents the soil index, and parameter "a" is determined by the slope of the fitted expression in the $VI$-$SI$ feature space ($a$ and the slope are reciprocal: $a \times k = -1$).

Landscape Element Extraction:
Landsat TM/OLI images were used for landscape element classification within the Mu Us Sandy Land from 1986 to 2020. The overall method and workflow remained consistent with the approach employed for the ARGON images. However, the high-resolution and low-resolution image combination shifted to $DDI$ and WorldView-2 imagery for the TM images. Similarly, for the OLI images, the high-resolution and low-resolution combination transitioned to $DDI$ and drone imagery acquired during the OLI period.

Cultivated land extraction utilized the random forest classification algorithm. Water bodies and residential areas were classified using the normalized difference water index ($NDWI$) and normalized difference built-up index ($NDBI$), respectively, calculated as follows:
where $G$ and $NIR$ represent the green and near-infrared bands of the TM/OLI image, respectively, and $NDWI$ represents the normalized difference water index.

$$NDWI = \frac{G - NIR}{G + NIR}$$

where $NIR$ and $SWIR$ represent the near-infrared band and shortwave infrared band of the TM/OLI image, respectively, and $NDBI$ represents the normalized difference built-up index.

Integrating these methods generated a comprehensive distribution map of landscape element types for the Mu Us Sandy Land from 1963 to 2020 (Figure 4).

3.3.4. Accuracy Assessment of Landscape Classification Results

Ground truth points were established to verify the classification accuracy of the landscape elements across the period of 1963–2020. The verification points leveraged vegetation cover information within 30 m grids calculated from corresponding high-resolution imagery across diverse Mu Us Sandy Land locations for the fixed, semi-fixed, and shifting sand land categories. These points were strategically chosen within the uniform areas of each landscape type to minimize the inclusion of boundary regions. Additionally, due to the cultivated land, water areas, and residential areas having well-defined boundaries and visual characteristics, the actual verification points were directly selected on high-resolution imagery for these categories.

The verification point selection for 2020 incorporated data from two sources: 326 ground vegetation survey quadrats and 141 verified field locations of cultivated land.
These were supplemented with additional verification points established using high-resolution Google Earth imagery. Table 1 provides a detailed breakdown of the verification point numbers for each image.

Table 1. Number of accuracy verification points based on different images.

<table>
<thead>
<tr>
<th>Image Types</th>
<th>Fixed Sandy Land</th>
<th>Semi-Fixed Sandy Land</th>
<th>Shifting Sandy Land</th>
<th>Cultivated Land</th>
<th>Water Area</th>
<th>Residential Area</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARGON</td>
<td>157</td>
<td>116</td>
<td>149</td>
<td>129</td>
<td>81</td>
<td>39</td>
<td>671</td>
</tr>
<tr>
<td>MSS</td>
<td>104</td>
<td>126</td>
<td>140</td>
<td>136</td>
<td>56</td>
<td>32</td>
<td>594</td>
</tr>
<tr>
<td>TM</td>
<td>104</td>
<td>110</td>
<td>122</td>
<td>111</td>
<td>102</td>
<td>85</td>
<td>634</td>
</tr>
<tr>
<td>OLI</td>
<td>108</td>
<td>80</td>
<td>81</td>
<td>181</td>
<td>31</td>
<td>119</td>
<td>741</td>
</tr>
</tbody>
</table>

Quantitative Accuracy Analysis:

This study employed a combination of ground verification points and confusion matrices to assess the reliability of the landscape classification results quantitatively. The overall accuracy (OA) and Kappa coefficients were calculated to evaluate the classification accuracy for the Mu Us Sandy Land. The relevant formulas are presented below:

\[
OA = \frac{\sum_{i=1}^{k} N_{ii}}{N}
\]

\[
Kappa = \frac{N \sum_{i=1}^{k} N_{ii} - \sum_{i=1}^{k} N_{i}+ N_{+i}}{N^2 - \sum_{i=1}^{k} N_{i}+ N_{+i}}
\]

where \( N \) represents the total number of samples, \( k \) represents the total number of categories in the classification result, \( N_i \) represents the number of samples incorrectly classified, and \( N_+i \) and \( N_i+ \) represent the number of actual samples and predicted samples for the \( i \)-th category, respectively.

Table 2 presents the accuracy verification results. The OA and Kappa coefficients for the classifications based on various images from 1963 to 2020 demonstrate high accuracy, indicating the classification methods’ effectiveness and suitability for analyzing long-term landscape dynamics within the Mu Us Sandy Land.

Table 2. Accuracy verification results of landscape classification.

<table>
<thead>
<tr>
<th>Image Types</th>
<th>OA/%</th>
<th>Kappa</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARGON</td>
<td>78.35</td>
<td>0.73</td>
</tr>
<tr>
<td>MSS</td>
<td>87.21</td>
<td>0.84</td>
</tr>
<tr>
<td>TM</td>
<td>90.38</td>
<td>0.88</td>
</tr>
<tr>
<td>OLI</td>
<td>82.67</td>
<td>0.79</td>
</tr>
</tbody>
</table>

4. Results

4.1. Overall Changes in Landscape Element Areas

Examining the landscape classification results for the Mu Us Sandy Land from 1963 to 2020 (Figure 4) reveals significant alterations in the landscape type distribution since 1963 (Figure 5). Fixed sandy land, semi-fixed sandy land, and shifting sand land constitute the primary elements of the Mu Us Sandy Land system, collectively exceeding 90% of the total area. Consequently, changes within these three categories dominate the overall landscape change process.

The area of fixed sandy land exhibited a distinct turning point around 1986, transitioning from a decreasing trend to an increasing one. From 1963 to 1986, the area declined from 8928.5 km\(^2\) to 2955.7 km\(^2\), dropping its proportion within the study area from 23.27% to 9.91%. Conversely, the period from 1986 to 2020 witnessed a fluctuating increase, resulting in an area of 12,107.8 km\(^2\) and a corresponding share of 31.55% of the total study...
area. The semi-fixed sandy land displayed a consistently increasing trend throughout the study period. Its area grew from 13,675.2 km² to 17,798.5 km², with a proportional increase in the study area from 35.64% in 1963 to 46.38% in 2020. The area of shifting sand land demonstrated an opposing trend compared to the fixed sand. It increased from 12,865.5 km² to 17,848.3 km² between 1963 and 1986, with its share of the study area rising from 33.53% to 46.51%. However, during 1986–2020, the area of shifting sandy land decreased significantly to only 3771.7 km², representing just 9.83% of the total area.

The cultivated land area generally decreased from 1963 to 1986, declining from 2568.9 km² to 1992.86 km². However, a slight increase was observed between 1986 and 2007, bringing the area to 2453.4 km². Notably, the period from 2007 to 2020 witnessed rapid growth, with the area expanding to 4065.3 km² in 13 years. The water area exhibited a generally fluctuating downward trend throughout the study period, decreasing from 333.4 km² in 1963 to 246 km² in 2020. Residential area changes can be categorized into two stages: a slow growth stage from 1963 to 2003 (increasing from 3.49 km² to 55.1 km² with an average annual increase of 1.29 km²) and a rapid growth stage from 2003 to 2020 (rising to 385.64 km², with a nearly sixfold expansion in the residential landscape area within 17 years).

**Figure 5.** Landscape element area changes in the Mu Us Sandy Land (1963–2020).

4.2. **Landscape Element Type Conversions**

Understanding the mutual conversion relationships among the landscape element types offers valuable insights into the changing dynamics of the Mu Us Sandy Land system across different periods. To explore these characteristics, transfer matrices were calculated for the landscape spatial distribution across ten periods from 1963 to 2020. These matrices quantify the transformations among the various landscape elements (Figure 6).

Considering 1986 as a turning point in the landscape element type area changes, we analyzed the transfer rates among the main elements during two periods: 1963–1986 and 1986–2020.

From 1963 to 1986, the most significant conversion feature involved the transformation of fixed sand to semi-fixed sandy land, accompanied by a substantial transfer of semi-fixed sandy land to shifting sandy land (Figure 6 a–c). During this period, fixed sand exhibited an average transfer-in rate of 43.51% and a transfer-out rate of 61.14%, while shifting sandy land had average transfer-in and transfer-out rates of 28.38% and 20.19%, respectively. Semi-fixed sandy land served as a bridge between fixed sandy land and
shifting sandy land, with average transfer-in and transfer-out rates of 39.07% and 37.28%, respectively.

The dominant conversion pattern reversed from 1986 to 2020 (Figure 6d–j). This period witnessed a continuous transfer of shifting sandy land to semi-fixed sandy land, followed by a large-scale conversion of semi-fixed sandy land to fixed sandy land. The average transfer-in and transfer-out rates for fixed sandy land during this period were 44.54% and 32.35%, respectively. Shifting sandy land exhibited average transfer-in and transfer-out rates of 10.94% and 27.97%, respectively, while semi-fixed sand had average transfer rates of 27.94% and 26.4%, respectively.


The contrasting conversion characteristics observed in the two periods highlight the influence of external factors (such as excessive cultivation, overgrazing, excessive logging, and climate change). Before 1986, a significant portion of the fixed sandy land area was converted to other types, while a large amount of land transitioned to shifting sandy land. This trend drove substantial changes in the landscape pattern within the study area. Conversely, the post-1986 period witnessed a reversal in the conversion pattern, with semi-fixed and shifting sandy land continuously converting to fixed sandy land. This shift significantly impacted the area distribution of landscape elements and the overall landscape pattern of the Mu Us Sandy Land.

5. Discussion

Landscape pattern changes typically result from natural and human influences [39,40]. Variations in weather elements, such as precipitation, temperature, and wind speed, can have some impact on landscape patterns. However, the most significant changes are usually associated with human activities related to land use and land cover (LULC). Human actions like land reclamation, overgrazing, deforestation, and urban
expansion can intensify land use and lead to rapid changes in the surface landscape [19,41]. On the other hand, initiatives such as ecological restoration, policies protecting pastures, and diversifying residents’ income sources can encourage sustainable land use practices and contribute to more stable ecosystems. Artemisia ordosica communities dominate the vegetation cover in the Mu Us Sandy Land.

Increased regional precipitation and temperature can promote vegetation growth, leading to increased surface vegetation cover and reduced wind-blown sand activity. Conversely, decreased precipitation and temperature can degrade vegetation, reduce vegetation cover, and increase wind-blown sand activity [42,43]. Notably, the annual average temperature in the Mu Us Sandy Land’s hinterland exhibited a warming trend (0.25 °C/decade) from 1960 to 2009, while yearly precipitation declined by 11.38 mm/decade during the same period, indicating a trend of warming and drying [32,44]. However, some studies suggest that the annual average temperature has fluctuated upward since the 1960s, with no evident trend in average yearly precipitation [45]. To assess potential climatic drivers of landscape change, we analyzed data on temperature, precipitation, and wind speed recorded at meteorological stations in the Yuyang District (eastern Mu Us Sandy Land) and Etuoke Banner (western Mu Us Sandy Land) since 1960. The spatial variations in these climatic parameters (east vs. west) exhibited no significant correlation with the overall trends observed in the landscape element type changes (Figure 7). This finding is consistent with previous research indicating a minimal impact of climatic factors on landscape dynamics in the study area.

The results of this study reveal a significant shift in the landscape within the Mu Us Sandy Land, with a turning point around 1986. This period coincides with a dramatic change in the landscape system pattern. Notably, the observed changes in the landscape pattern since the 1960s appear to be primarily independent of climatic variations. Consequently, climatic factors are unlikely to be the primary driver of the landscape pattern shift observed around 1986.

With social productivity and population growth advancements, human activities have become a powerful force shaping landscape patterns. Several studies examining long-term land cover changes within the Mu Us Sandy Land highlight the impact of policy factors during the 1950s and 1970s. These unscientific or irrational land use policies are linked to significant grassland loss and increased unused land within the region [46]. Additionally, the rapid rise in livestock populations within the pastoral areas during the 1960s, driven by policy decisions, is documented to have caused rapid vegetation degradation on sandy land [47,48]. This degradation ultimately led to severe land desertification and fueled the expansion of mobile sandy lands within the pastoral areas during this period.

Following China’s reforms initiated in 1978, ecological protection gained increasing attention. The Chinese government subsequently implemented a series of ecological
restoration projects, exemplified by the Three-North Shelterbelt Development Program in the Mu Us Sandy Land. These projects aimed to optimize land use through various initiatives, including afforestation programs, enhanced pasture protection measures, natural forest resource conservation, and strict enforcement of grazing bans. These initiatives were crucial in restoring vegetation cover within the study area’s agricultural and pastoral areas. Notably, the area of fixed sandy land witnessed a significant increase.

To quantify the impact of these projects, we analyzed the cumulative implementation area of ecological restoration projects within Ordos City, encompassing the Mu Us Sandy Land region, since the year 2000. The results reveal a rapid increase in the implementation area of the six major ecological restoration projects since 2000. By 2020, 60.71% of the region’s land had received investments in ecological restoration projects (Figure 8).

Previous research has examined landscape pattern changes within the Mu Us Sandy Land pastoral area between 1990 and 2014. The analysis demonstrated an increase in landscape complexity during this period, characterized by a rise in patch number, a decrease in the average patch area, and increased fragmentation [33]. These findings highlight the significant landscape changes within the Mu Us Sandy Land since 1990, aligning with the observed dramatic shift in landscape change patterns after 1986.

While remote sensing imagery spanning the period since 1963 offers valuable insights into the evolution of landscape element types within the Mu Us Sandy Land, the driving forces behind these changes likely vary across different timeframes and spatial regions. A fundamental limitation of this study lies in the discontinuity of specific crucial indicator data, such as the spatial distribution of ecological restoration projects, over such an extended timeframe. The inherent challenges associated with spatializing and potentially missing data necessitate the application of an observational comparison method for analyzing the drivers of landscape change instead of the spatial measurement method in this work. Future research endeavors will prioritize collecting more continuous, spatially explicit data to enable a more robust investigation of the driving mechanisms behind landscape change, potentially incorporating deep learning or AI technologies. Additionally, the significant fluctuations in the cultivated land area observed within the Mu Us Sandy Land during the 1950s-1970s serve as a strong indicator of intensified human activities. Understanding the changing characteristics of cultivated land is crucial for deciphering
the evolution of the landscape pattern during this period. We have written relevant articles to analyze the relationship between cultivated land changes, vegetation degradation, and landscape evolution, which are detailed in separate publications.

6. Conclusions

Landscape Dynamics: The Mu Us Sandy Land experienced significant landscape transformations from 1963 to 2020. Fixed and semi-fixed sandy land exhibited a U-shaped change pattern, initially decreasing and increasing in area. Conversely, shifting sandy land displayed an inverted U-shaped pattern, first increasing and then decreasing. The eastern region of the Mu Us Sandy Land witnessed a particularly prominent shift, transitioning from shifting sandy land dominance to fixed sandy land dominance. Furthermore, the changes in cultivated land, water areas, and residential areas reflected the interplay between natural factors and human activities. Cultivated land areas exhibited a biphasic trend, initially declining and then experiencing a rapid increase. The water areas demonstrated a generally fluctuating decrease, while the residential areas substantially expanded.

Landscape Conversion Patterns: Analysis of landscape element type conversion revealed 1986 as a critical turning point for desertification processes in the Mu Us Sandy Land. Before this year, fixed sandy land primarily transformed into semi-fixed sandy land, and semi-fixed sandy land underwent large-scale conversion into shifting sandy land. This trend reversed entirely after 1986. These transformations significantly impacted the area and spatial distribution of landscape elements. Overall, the landscape change from 1963 to 1986 was characterized by shifting sandy land expansion and fixed sandy land reduction, while the period from 1986 to 2020 witnessed a reversal, with decreasing shifting sandy land and increasing fixed sandy land as the dominant trends.

Drivers of Landscape Change: Since 1963, the dramatic landscape alterations in the Mu Us Sandy Land did not directly correlate with climate element trends. The temperature and precipitation patterns did not consistently favor mobile sand reduction. Therefore, climate factors cannot be considered the primary drivers of landscape change in the Mu Us Sandy Land during this period. Instead, human interventions, particularly large-scale ecological restoration projects like the Three-North Shelterbelt Development Program, Grain for Green Program, and Returning Pasture to Grassland Program, were implemented with continuous and intensive investment by the Chinese government after the 1980s, and have emerged as the main driving forces behind the substantial changes observed in the landscape elements of the Mu Us Sandy Land.

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