Characteristics of spatial pattern evolution of blowouts in the Hulunbuir sandy grassland

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Abstract. Blowout is the initial form of sand steppe, sand belts, or dunes; the continuous development of blowouts leads to desertification expansion and ecological degradation. The study area is a typical blowout area of 30762 hm² near a sand belt north of the Hulunbuir Grassland. Seven images from Landsat TM (30 m) taken in 1984, 1990, 1995, 2000, 2005, 2010, and 2016 were analyzed using ArcGIS and FRAGSTATS software and the landscape pattern index method to investigate the spatial pattern change of blowouts. The results show that the distribution of blowouts is intensive, primarily comprising blowouts <10 hm², with the largest blowout in the study area being equal to 96.59 hm². There was a significant correlation among blowout patch area, shape index, and fractal dimension. The long axis of the blowouts is consistent with the prevailing wind. As the blowout area increases, it forms a saucer-trough irregular shape. In summary, although there is a wide blowout distribution, there is a local aggregation distribution in certain areas resulting in significant landscape fragmentation. As a result, there is a risk of blowout fragments forming a large area of sandy land or partially broken sand dune landforms. To prevent desertification, corresponding measures for vegetation restoration should be implemented during early-stage blowouts.

1. Introduction

The Hulunbuir Grassland is characterized by fixed wind erosion surface, activation, and grassland desertification, and its surface characteristics include patch breakage, spread, local desertification, and blowout formation. Among them, the blowout of sandy grassland is a typical geomorphic unit in Hulunbuir Grassland sandbelt, which directly affects vegetation and other surface processes and leads to the complexity and heterogeneity of the landscape pattern in the grassland-sandbelt area. As an important aeolian landform type in arid and semi-arid sandy grasslands, blowouts have become an important cause and process of grassland desertification [1]. Therefore, studying the spatial distribution pattern, occurrence, and development process of blowouts has a wide application value for guiding effective policy for the prevention and control of further desertification of sandy grasslands. In recent years, many domestic scholars have systematically studied the development process [2–3], morphological characteristics [4–5], influencing factors [6–7], and surface airflow characteristics [8–9]...
of blowouts in sandy grasslands. As a special type of landform, the increase in the number and area of blowouts will inevitably have an important impact on grassland ecology. The spatial pattern and characteristic analysis of blowouts in sandy grasslands based on ALOS (Advanced Land Observing Satellite) satellite image data [10], as well as the study of landscape transfer transformation between sandy land and other land types in grassland areas [11], can provide a scientific reference for the decision-making of grassland desertification prevention and control.

The evolution of landscape patterns is the result of interactions between abnormal environmental changes and human activities [12–13]. In response to the Suggestions on Taking Emergency Measures to Restrain Desertification of Hulunbuir Grassland and Suggestions on Special Governance of Hulunbuir Sandy Land in Inner Mongolia presented by Hong Fuzeng and other grassland experts [14], the Grassland Restraint and Grassland Prohibition Project was launched by the city of Hulunbuir and the National Natural Grassland Returning Grassland to Grassland Project has been implemented in four counties with pasture areas since 2000 [15]. The effectiveness of these various ecological protection projects and their impacts on the regional landscape pattern are yet to be investigated. Scientific data are needed to for analysis and verification, and a clear and concise mathematical method is required to depict the complicated evolution process. Landscape metrics is an appropriate and desirable method for this task.

Chen Barag county is located in the northwest of Hulunbuir City, Inner Mongolia. It is also located in the hinterland of the Hulunbuir Grassland. The east and northeast of the county are bordered by Yakeshi City and Erguna City, respectively; the southeast is bordered by the Hailar Area; the south is bordered by the Ewenki Zizhiqiq; the west is bordered by Xin Barag Zuoqi, and the northwest faces Russia across the Erguna River. The study area, located in Chen Barag county, is a typical blowout area (Figure 1), a sandy grassland zone between the southern bank of the Hailar River and the northern sand belt of Hulunbuir Sandland (Hailar Valley Sand Belt). It is located in a rectangular area southeast of Wangong town (118°52′48″–119°21′00″E, 49°07′12″–49°12′00″N), west of Manzhouli City, and east of the Hailar Area. The east–west length of the image is approximately 86.85 km and the total area is approximately 305 km².

Figure 1. Sketch map of the study area

With an elevation of 600–800m, the study area has a semi-arid grassland climate with Annual accumulated temperature ranges from 1600-3400°C. The annual precipitation ranges from 280–400 mm.
It is dry, cold, and windy. The predominant wind direction is southwest and west. The soils in the area are mainly aeolian sand, mainly concentrated in the desertification zone and the surrounding sandy grassland, with low soil fertility. The dominant natural zonal plants in sandy grasslands are *Leymus chinensis*, *Agropyron criatatum*, and *Cleistogenes squarvosa*. Seasonal annual plants, such as *Agriophyllum punge*, *Salsola collina*, and *Salsola collina*, are distributed in a single community, forming a unique sandy grassland vegetation community [16].

2. Data Source and Method

2.1. Data Sources and Processing

2.1.1. Remote sensing image data and processing. The Landsat TM (a spatial resolution of 30 m) historical images provided by BIGEMAP Downloader is the main data source, which was divided into seven periods 1984, 1990, 1995, 2000, 2005, 2010, and 2016. The coordinate projection is the China Geodetic Coordinate System 2000.prj. Using ArcGIS software, the image was visually interpreted based on the keys of visual interpretation [4] (Table 1), and an image map and the vector distribution of blowouts in the study area were obtained (Figure 2).

| Keys of Interpretation | Characterization |
|------------------------|------------------|
| The area with light green, dark green and red background is grassland. |
| Blowouts are shiny white or yellowish with different shapes and obvious development boundaries. |
| All the bright white sand in the blowout is bare sand without vegetation growth. The yellow soil and sporadic yellow-green soil in the blowouts are vegetation restoration growth. |
| Most blowouts have a long axis in the same direction as the main wind. |

The blowouts interpreted by remote sensing in this study include blowouts formed on sandy grasslands, sand accumulation behind blowouts, and bare wind erosion land. The Spatial Analysis module of ArcGIS10.1, was used to transform the vector data shape file into a raster data raster file (the output pixel size is 10 × 10 m) [17–18] and to analyze the spatial distribution pattern change.
2.1.2. *Field Data Acquisition*. According to the preliminary interpretation results of the remote sensing images, two sample areas with a size of $2 \times 2$ km were set in an area with typical blowout distribution, and selected 15 blowouts in the sample areas, the accuracy of interpretation is up to 95.6% compared with the image interpretation results. Morphological parameters such as length, width, depth, area, and circumference of blowouts were measured using hand-held GPS, rope measuring, box staff, and other tools, and the topographic position, shape, and growth status of vegetation on the ground were recorded in the field. Among the investigated blowouts, only two were composed of blowouts with rear end sand deposits and the rest were free of rear end sand deposits. Therefore, the measured morphological parameters of blowouts in this study do not include rear end sand deposits.

2.2. *Landscape Pattern Index Analysis Method*

Using the landscape pattern index results from the condensation and extraction of landscape information the landscape structure and type structure can be mapped. According to the index classification of Fragstats software, the pattern index is divided into four types: (1) the area, perimeter, and density metrics, (2) shape metrics, (3) contagion metrics, and (4) diversity metrics. Different landscape pattern indices reflect different information, but some landscape pattern indices have a strong correlation. Landscape indices with strong correlations in repeated selection tend to cause data redundancy [19–20]. The metrics of area, density, and diversity for the landscape index at 11 class levels in the first two types were selected [10, 21] to analyze the spatial distribution pattern of the blowouts in this study. Landscape pattern analysis software Fragstats 3.4, was used to calculate 11 landscape pattern indices in the image area at the landscape level. Landscape index analysis was completed using SPSS17.0 software. This method compares the time series and the space series of various landscape indices in different historical time image areas to analyze the dynamic evolution of the landscape pattern. It combines the ecological evolution process of the area with changes in the landscape pattern to analyze the changes in landscape structure and spatial allocation of land types in the research area over the past 30 years to assist the follow-up study and policy recommendations.
### 3. Result and Analysis

#### 3.1. Characteristics of Size Change of Blowouts

The total study area is 30762.25 hm$^2$. In 2016, the patch quantitative characteristics of blowouts (Table 2) showed that the number of patches (blowouts) in the study area was 87.

#### Table 2. Patch quantitative characteristics of blowouts

| Number of Patches (NP/pieces) | Patches Area (CA/hm$^2$) | Mean patch area (MPS/hm$^2$) | Total Area (TA/hm$^2$) | Percentage of Landscape (PLAND/%) |
|-------------------------------|--------------------------|-----------------------------|------------------------|---------------------------------|
| 87                           | 1267.26                  | 14.57                       | 30762.25               | 4.12                            |

The mean patch area refers to the total area of a single landscape type divided by the number of patches, which reflects the degree of landscape fragmentation. The smaller the value, the more fragmented the landscape is [22]. The mean patch area was 14.57 hm$^2$ with a total area of 1267.26 hm$^2$, accounting for 4.12% of the landscape area (Table 3). After the field investigation, the interpretation accuracy was verified as 91.8%. According to the patch data statistics, 41 patches with an area of 10–100 hm$^2$ accounted for 47% of the total blowouts number; 46 blowouts with an area of $<$10 hm$^2$ accounted for 53% of the total blowouts number. The number and area of patches reflect the characteristics of the blowout size, it indicated new blowouts are constantly occurring in Hulunbuir sandy grassland.

#### Table 3. The dynamic change of blowouts

| Landscape pattern index | 1984 | 1990 | 1995 | 2000 | 2005 | 2010 | 2016 |
|-------------------------|------|------|------|------|------|------|------|
| Number of patches/pieces | 83   | 78   | 75   | 96   | 117  | 96   | 87   |
| Mean patch area/hm$^2$   | 287.62 | 274.47 | 642.88 | 665.62 | 794.79 | 885.54 | 1267.26 |
| Percentage of landscape/%| 0.93 | 0.89 | 2.09 | 2.16 | 2.58 | 2.88 | 4.12 |

Table 3 presents the changes in the number of patches (blowouts), mean patch area, and the percentage of the landscape comprising blowouts from 1984 to 2016. It can be seen that from 1984 to 2005, the number of patches increased continuously, and the mean patch area and the percentage of landscape also increased year on year. It can be seen that wind erosion continuously deteriorated and aggravated the landscape during this period. However, during 2005–2016, although the number of patches showed a downward trend, two landscape indices, mean patch area and the percentage of landscape, maintained an upward trend. This implies that wind erosion continuously increased resulting in the merging of blowouts and therefore a reduction in the number of patches. This is supported by previous studies which investigated blowout evolutionary processes.

#### 3.2. Characteristics of Distribution Pattern Change of Blowouts

In 2016, the patch density of the blowout in the study area was 0.28 pieces/hm$^2$, and the mean proximity index was 55.042 (within the 1000 m search radius), which indicates the connectivity between the patches (Table 4). The larger the patch density value, the stronger the connectivity between the same type of patch [23]. The mean nearest distance was 89.078 m.

#### Table 4. Patch distribution characteristics of blowouts

| Patch Density (PD/pieces hm$^2$) | Mean Proximity Index (AW_MPI) | Nearest Distance Mean (MNN/m) |
|----------------------------------|-------------------------------|-----------------------------|
| 0.28                             | 55.042                        | 89.078                      |
The density values of the patches ranged from 0.2–0.4, indicating that most of the blowouts consist of large patches. The distance between patches reflects the distribution density and development trend of the blowouts. As the distance between the blowouts decreases, the distribution density and landscape fragmentation increases, and the risk of blowout patches connecting to form a large area of sandy land or a partially fragmented sand dune increase. Overall, since 1984, the landscape fragmentation of blowouts has been decreasing, and the mean nearest distance has also decreasing year on year, which is consistent with field observations in which the wind erosion desertification has continuously intensified, and the blowouts appear to expand and consolidate centrally and continuously.

3.3. Characteristics of Morphological Changes of Blowouts

The patch shape characteristics of blowouts are presented in Table 5. The mean fractal dimension index of the blowouts was 1.049, and the patch area coefficient of variation was 1.317, indicating that the shapes of most of the blowouts were relatively simple. With an increase in the area of the blowout, its shape changed regularly. The patch area coefficient of variation is the ratio of the perimeter of the patch to the perimeter of the same area circle, which is mainly used to represent the degree of regularity of the patch shape. The larger the value, the more irregular the patch shape in the landscape. The landscape shape index determines the complexity of the landscape from its shape, while the area-weighted fractal dimension includes the information reflected by the average perimeter area ratio, and measures the complexity of the mosaic structure of landscape elements from the perspective of self-similarity[24]. Through the function model verification, there was no significant correlation between the patch area of blowout and shape index, fractal dimension, and the Pearson correlation coefficient was less than 0.060 (P = 0.000). This shows that with the increase in the area, the shape of the blowout develops from simple to complex, but the correlation coefficient between them is less than 0.75 [10]. Therefore, there was no significant correlation between the two indicators.

Table 5. Patch shape characteristics of blowouts

| Mean Fractal Dimension index (FRAC_MN) | Patch Area Coefficient of Variation (AREA_CV) | Shape Index Mean (AW_MSI) |
|---------------------------------------|-----------------------------------------------|--------------------------|
| 1.049                                 | 1.258                                         | 1.317                    |

Moreover, through data comparison, it was found that the shape index and fractal dimension of the largest patch were not the largest, but only fell in the middle and upper levels. This may be due to the fact that after several blowouts are connected to form a large and complex blowout, its edge is rounded under the action of wind erosion and finally reaches a new stable period. By superimposing the vector layers of the blowouts over seven years (Figure 3), it can be concluded that the long axis of the blowouts in the study area is basically consistent with the local prevailing wind direction, and after forming the blowouts develop along the prevailing wind direction (westerly or southwesterly).
Figure 3. Dynamic changes of shape, displacement and direction of blowouts

The development and change types of wind erosion pits can be summarized as follows: (1) Primary stage - Bare sand saucer shaped blowouts(Figure 3a.), with a shape index value of approximately 1 and an area generally less than 0.1 hm$^2$. After local vegetation is destroyed, a disc-like surface exposed with an obvious boundary is formed, and its depth generally does not exceed 0.5 m. (2) Active development stage - Ellipse-shaped blowouts(Figure 3b.), the most typical shape type in this area. Under the action of further erosion by strong winds, deep and large elliptical or oval blowouts are formed along the direction of the prevailing wind. (3) Fixed stage-Trough-shaped blowouts(Figure 3c.), because of the influence of vegetation or site conditions, the lateral development of blowouts is limited, and rectangular or trough-shaped blowouts are formed along the long axis direction. They are mainly distributed along abandoned roads or on-site feeding areas on both sides of highways and railways. Usually, their scale and depth change significantly. (4) Reactivation stage-composite-shaped blowouts(Figure 3d.), this can be regarded as the final form of blowout development. After the fixed stage, the shape of a single blowout is generally irregular. The irregularity endures during the process of two or more blowouts enlarging and merging. There are undulating terraces or wind erosion columns in the connection blowout. At this stage, the blowouts have a large area, and may develop into desertification.
4. Discussion

4.1. Scale Change of Blowouts

The study area is near the sand belt in the north of Hulunbuir Grassland, which is a transition area from sandy land to typical grassland. During the field investigation, it was found that blowouts in Hulunbuir grassland had rear side sand deposition the morphological development process of which requires further study. The depth of the blowouts in the study area is within 0.5–12 m, both length and width increase, so the area rapidly expands [3]. Once a blowout is formed, the areas of the blowout will be enlarged by further wind erosion. This process occurs in two ways: (1) the area of the independent blowout is enlarged to a certain value; the blowout enters a fixed or stable stage owing to the resistance of the bottom soil layer and surrounding vegetation and the change of local air flow in it. (2) Relatively dense blowouts form under certain site conditions; adjacent blowouts are joined to form large-area blowouts with the continuous expansion of a single area. Based on remote sensing interpretation and field measurement data, it can be concluded that the area of this type of blowout is generally larger than 10 km².

From the remote sensing interpretation results, the complex shape of blowout patches in Hulunbuir sandy grassland is mainly formed by enlarging and connecting several independent blowouts. Investigation and research on sand grassland blowouts in Hulunbuir by Zhang Deping et al.[4]. found that blowouts, such as palm-shaped and flower-shaped blowouts, form during the reactivation phase after a single blowout is fixed. In addition, some blowouts with large areas and complex shapes in this study also show similar features in the texture and color of remote sensing images as those research results of Zhang Deping et al.

4.2. Limitations: Image Resolution for Evolution Analysis Blowouts

(1) Using Landsat TM (spatial resolution 30 m) image data, the spatial distribution and characteristics of blowouts on a sandbelt in Hulunbuir Grassland were analyzed at the landscape scale. However, because of the limitation of image resolution, the dynamic change in the landscape pattern of smaller blowouts cannot be investigated, which needs to be further studied by using higher resolution remote sensing data.

(2) This study only analyzed specific landscape pattern characteristics for a single type of blowout in a sandy grassland area, without considering other land use types such as residential areas, roads, water bodies, etc. A follow-up study will conduct a more comprehensive investigation into the landscape pattern characteristics for various land use types.

5. Conclusion

● Blowouts in Hulunbuir Sandy Grassland are densely developed, accounting for 4.12% of the total area. The patch density was 0.28 pieces·hm⁻². The number of patches with an area below 10 hm² was equivalent to that with an area between 10 and 100 hm². In 2016, the largest area of blowout in the study area was 96.59 hm², which is far beyond the traditional concept of blowouts and reflects the seriousness of wind erosion and desertification in the Hulunbuir Grassland.

● The long axis of the blowout is consistent with the prevailing local wind direction. With an increase in the area, the shape pattern of the blowouts can be summarized as follows: saucer-ellipse-trough-irregular shape. There is a significant correlation between the patch area of the blowout, shape index, and fractal dimension. Landscape patches in the grassland area are developing toward fewer patches and more complex shapes. Landscape fragmentation was weakened, but the spatial connectivity of the landscape pattern decreased.

● The distribution of blowouts was extensive, but locally aggregated. The local landscape fragmentation of the Hulunbuir Grassland is relatively high, the style of blowout is typical, and there is a risk of forming a large area of sandy land or partially broken sand dune landforms comprised of blowouts. Therefore, corresponding measures for vegetation restoration should be adopted in the early stage of blowout formation to prevent further development of grassland desertification.
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