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Abstract

Desertification is a widespread ecological and environmental problem in arid and semi-arid regions. As an inland plateau in a typical arid and semi-arid climate zone, the Mongolian Plateau faces prominent desertification issues, profoundly affecting regional ecological security and sustainable socioeconomic development. Based on four dimensions—vegetation, climate, soil, and human activities—seven indicators were selected: normalized difference vegetation index, net primary productivity, precipitation, air temperature, soil moisture, soil organic matter, and population intensity. Indicator weights were determined using triangular fuzzy number theory and the analytic hierarchy process, and a multi-factor linear evaluation model was established. Combined with geographic information technology, a comprehensive assessment of desertification on the Mongolian Plateau was conducted. The results show that: (1) The vegetation dimension has the highest weight in the comprehensive evaluation (50.74%) and is the most direct response factor of desertification status. The climate dimension ranks second (25.18%), mainly reflecting the driving effects of precipitation and air temperature on ecosystems. The weights of the soil and human activity dimensions are 20.38% and 3.72%, respectively. (2) Areas with mild or higher levels of desertification on the Mongolian Plateau are mainly distributed in the southwest, accounting for approximately 83.4% of the total area. Among them, severe, moderate, and mild desertification areas account for 41.9%, 24.7%, and 16.8%, respectively. Non-desertified areas are mainly distributed in the north and northeast, accounting for 16.6%. (3) From 2001 to 2005, desertification on the Mongolian Plateau showed an overall worsening trend; from 2005 to 2020, it showed an improving trend; and from 2020 to 2023, it worsened slightly. (4) Precipitation is the most important driving factor affecting the evolution of desertification on the Mongolian Plateau. Rising air temperature indirectly promotes desertification by intensifying evaporation and drought processes, while human activities have significant impacts in local areas. (5) Regional comparison indicates that since 2001, desertification in Inner Mongolia Autonomous Region, China has generally improved, whereas desertification in Mongolia has tended to worsen, with the differences related to the ecological restoration policies and engineering measures of the two countries.

Full Text

Comprehensive Evaluation of Desertification in the Mongolian Plateau Based on a Multi-Factor Linear Model

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Abstract: Desertification is a widespread ecological and environmental problem in arid and semi-arid regions. As an inland plateau with a typical arid and semi-arid climate, the Mongolian Plateau has prominent desertification problems, which profoundly affect regional ecological security and sustainable socioeconomic development. Based on four dimensions–vegetation, climate, soil, and human activities–seven indicators were selected: normalized difference vegetation index, net primary productivity, precipitation, air temperature, soil moisture, soil organic matter, and population density. The triangular fuzzy number theory and analytic hierarchy process were used to determine indicator weights, and a multi-factor linear evaluation model was established. Combined with geographic information technology, a comprehensive evaluation of desertification on the Mongolian Plateau was conducted. The results show that: (1) The vegetation dimension had the highest weight in the comprehensive evaluation (50.74%) and was the most direct response factor for desertification status. The climate dimension ranked second (25.18%), mainly reflecting the driving effects of precipitation and air temperature on ecosystems. The weights of the soil and human activity dimensions were 20.38% and 3.72%, respectively. (2) Areas of slight desertification and above on the Mongolian Plateau were mainly distributed in the southwest, accounting for about 83.4% of the total area; among them, severe, moderate, and slight desertification areas accounted for 41.9%, 24.7%, and 16.8%, respectively. Non-desertified areas were mainly distributed in the north and northeast, accounting for 16.6%. (3) From 2001 to 2005, the overall degree of desertification on the Mongolian Plateau showed a worsening trend; from 2005 to 2020, it showed an improving trend; and from 2020 to 2023, it worsened slightly. (4) Precipitation was the most important driving factor influencing the evolution of desertification on the Mongolian Plateau. Rising air temperature indirectly promoted desertification by intensifying evaporation and drought processes, while human activities had significant effects in some local areas. (5) Regional comparison shows that since 2001, desertification in the Inner Mongolia Autonomous Region of China has generally improved, whereas in Mongolia it has shown an aggravating trend; the difference is related to the ecological restoration policies and engineering measures of the two countries.

Keywords: Mongolian Plateau; desertification; climate change; multi-factor linear model; spatiotemporal process

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Land desertification is a process of land degradation that occurs in arid, semi-arid, and dry sub-humid regions under the combined effects of climate change and human activities. It is mainly manifested as vegetation degradation, damage to soil structure, decreases in soil moisture and nutrients, and intensification of wind and water erosion. Desertification not only weakens ecosystem stability and ecological service functions, but also leads to declines in cropland productivity and increases in sandstorm disasters, affecting the sustainable development of regional socioeconomic systems. It is estimated that about 35% of the world' s land area is affected by desertification; each year, desertification causes about 2×10^7 hm^2 of cultivated land to degrade, grain production to decrease by 12%-21%, and annual losses to reach 2.61×10^{10} USD, severely constraining the sustainable development of global ecosystems[1]. Therefore, constructing a comprehensive evaluation system that can reflect the degree of desertification and its spatiotemporal evolution patterns, and revealing the relative contributions of various factors to the comprehensive index under long time-series conditions, are practical needs in desertification research and prevention practice.

Many scholars have carried out extensive research on the evolutionary process and evaluation methods of desertification. Research related to land desertification in China began in the 1980s[2]. Zhu Zhenda et al.[3] took the lead in establishing an evaluation system for desertification in northern China; with the degree of soil sandy expansion, the proportion of quicksand distribution, and surface landscape characteristics as its core, this system laid the theoretical foundation for desertification evaluation in China. Berry et al.[4] integrated multiple source factors such as climate, soil, and land-surface processes at the global scale and constructed a multi-level monitoring system for different scales. Reining et al.[5] further improved the desertification evaluation indicator system on this basis, incorporating physical, biological, and social factors into a unified framework. At the regional scale, Yan Feng et al.[6] took the Mu Us Sandy Land as the study area and carried out dynamic assessment of desertification through Landsat remote-sensing images. Wang Feng et al.[7], through field surveys, sediment particle-size and provenance analyses, and comprehensive assessment of climatic and ecological factors—

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study, analyzed the formation mechanisms and evolution processes of desertification in the Kubuqi Desert; Xi Lei et al. [8] constructed an indicator system covering climatic conditions, human activities, and the current status of desertification monitoring, used a subjective–objective combined entropy combination weighting method to establish a comprehensive evaluation index of desertification risk, and assessed the desertification risk in the Environmental Tower Basin. With advances in remote sensing, big data technologies, and cloud computing platforms, machine-learning algorithms such as support vector machines and random forests have also been increasingly applied in monitoring, opening up new pathways for the precise evaluation of desertification [9]. Meanwhile, the popularization and application of cloud computing platforms such as the Google Earth Engine have enabled people to monitor desertification at large scales and over long periods [10].

Although related research continues to advance, comprehensive evaluation of desertification on the Mongolian Plateau still has shortcomings: (1) Some studies focus on a single dimension, such as vegetation or climate, and insufficiently incorporate key factors such as soil moisture, soil organic matter, and the intensity of human activities, which affects a comprehensive depiction of regional desertification conditions. (2) In cross-year studies, evaluation standards and classification thresholds are inconsistent, weakening the comparability and stability of long time-series results. In addition, the interpretation of the relative importance of different factors within comprehensive indicators still needs to be strengthened. Based on this, this study selects the Inner Mongolia Autonomous Region of China and Mongolia as the study area of the Mongolian Plateau. From four dimensions—climate, soil, vegetation, and human activities—it selects seven indicators: normalized difference vegetation index (NDVI), net primary productivity (NPP), precipitation, air temperature, soil moisture, soil organic matter, and population intensity. A comprehensive desertification evaluation system is constructed, and expert scoring combined with the analytic hierarchy process is used to determine weights, forming a comprehensive evaluation index and classification results. To enhance interannual comparability, the 2023 evaluation results are used as the benchmark; the natural breaks method is used to determine classification thresholds, which are then applied uniformly to each year from 2001 to 2023, in order to characterize the spatiotemporal evolution of desertification. At the same time, the relative importance of each factor is quantitatively characterized, providing a reference for long-term monitoring and governance zoning of desertification on the Mongolian Plateau.

1 Data and Methods

1.1 Overview of the Study Area

This study selects the Inner Mongolia Autonomous Region of China and Mongolia as the study area of the Mongolian Plateau (87°43′-126°04′E, 37°46′-53°20′N). Based on boundary calculations, the total area is approximately 2.75×10^6 km^2 (Fig. 1). The terrain of the Mongolian Plateau is complex; the topography gradually decreases from west to east. The northwestern region is dominated by mountains, the central and eastern regions by hills, and the southwestern region by the vast Gobi Desert [11]. This region has a typical temperate continental climate, with mean annual precipitation of about 200 mm and relatively little precipitation. Annual temperature variation is large, showing pronounced spatiotemporal differences. Vegetation types are rich and

Fig. 1 Schematic diagram of the study area

Figure 1: Fig. 1 Schematic diagram of the study area

diverse, presenting a distinct zonal distribution pattern.

Note: Prepared based on the standard map from the Map Service Website of the Ministry of Natural Resources, approval number GS(2019)1822; the base-map boundary has not been modified. The same below.

Figure 1 Study area schematic diagram

Fig. 1 Schematic diagram of the study area

1.2 Data Sources

Four first-level indicators—climate, vegetation, soil, and human activities—and seven subordinate second-level indicators (precipitation, air temperature, NDVI, NPP, soil moisture, soil organic matter, and population intensity) were selected to construct the comprehensive desertification evaluation index for the Mongolian Plateau. In this paper, data from different sources were processed through clipping, interpolation, resampling, and other procedures, and finally annual data for the Mongolian Plateau with a resolution of $0.05° \times 0.05°$ were obtained (Table 1). When calculating area and other statistics, all data were unified under the projected coordinate system.

1.3 Research Methods

1.3.1 Triangular Fuzzy Number

As an important implementation form of fuzzy set theory, triangular fuzzy numbers are commonly used to express fuzziness and uncertainty in the evaluation process. They are generally represented as a triplet $P = (a, b, c)$, with the corresponding function:

$$p(x) = \begin{cases} \frac{x-a}{b-a}, & a \le x \le b \\ \frac{c-x}{c-b}, & b \le x \le c \\ 0, & \text{otherwise} \end{cases} \qquad (1)$$

where $p(x)$ is the membership function of the triangular fuzzy number P; x is the independent variable; a is the lower bound of the fuzzy number; b is the most possible value; and c is the upper bound of the fuzzy number. Defuzzification is then performed:

$$G = \frac{a + 4b + c}{6} \qquad (2)$$

where G is the deterministic evaluation value after defuzzification.

Triangular fuzzy numbers provide an effective method for reducing the influence of experts' subjective judgments on results and are widely applied in multi-attribute evaluation and fuzzy decision-making. In this paper, on the basis of experts' scoring of second-level indicators, triangular fuzzy numbers are used to fuzzily synthesize the scoring results.

Table 1 Evaluation indicators and data sources

Tab. 1 Evaluation indicators and data sources

Indicator	Source	Spatial resolution	Temporal resolution	Source
Air temperature/°C	CRUTS dataset	0.5°(×)0.5°	Annual mean	https://crudata.uea.ac.uk/cru/data/hrg/
Precipitation/mm	TerraClimate dataset	1/24°	Annual total	https://www.climatologylab.org/terraclimat
NDVI	Modis dataset	0.05°(×)0.05°	Annual mean	https://lpdaac.usgs.gov/products/mod13c1
NPP/g C · m^-2	Modis dataset	500 m	Annual mean	https://lpdaac.usgs.gov/products/mod17a3
Soil moisture/mm	TerraClimate dataset	1/24°	Annual mean	https://www.climatologylab.org/terraclimat
Soil organic matter/%	HWSD dataset	30″	Fixed value	https://gaez.fao.org/pages/hwsd
Total population/persons	LandScan dataset	30″	Annual value	https://landscan.ornl.gov/

Note: NDVI is the normalized difference vegetation index; NPP is net primary productivity; the soil moisture-content data are the total amount of water stored in the soil column of the effective root zone of the entire plant; population data (originally the population per grid cell) are used to characterize population intensity after unification to a common grid. The same below.

1.3.2 Analytic hierarchy process

This paper uses the analytic hierarchy process to determine the weights of each indicator. By comparing the relative importance of every two indicators by experts, a judgment matrix is constructed (Table 2), and the nine-point ratio scale (Table 3) is used to evaluate the relative importance of the indicators[1]. A value of 1 indicates that two indicators are equally important; 3, 5, 7, and 9 respectively indicate that the former is slightly more important, important,

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very important, and extremely important than the latter; 2, 4, 6, and 8 indicate intermediate values between adjacent judgment levels; an evaluation value greater than 1 indicates that the former is more important than the latter, and a value less than 1 indicates that the former is less important than the latter, with its value being the reciprocal of the corresponding judgment value.

To ensure the consistency of expert judgments, a consistency test should be carried out on the corresponding pairwise-comparison matrix. First, the consistency index (CI) is calculated:

$$\mathrm{CI} = \frac{\lambda_{\max} - m}{m - 1} \qquad (3)$$

where $\lambda_{\max}$ is the maximum eigenvalue of the matrix, and m is the order of the matrix.

The consistency is tested using the consistency ratio (CR):

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \qquad (4)$$

where RI is the random consistency index. When $\mathrm{CR} < 0.1$, it indicates that the matrix satisfies the consistency requirement; if the standard is not met, expert scoring must be adjusted and the matrix reconstructed. After passing the consistency test, according to the pairwise-comparison matrix (A), the weights are determined by solving the following eigenvalue problem:

$$Av = \lambda_{\max} \times v \qquad (5)$$

$$w_i = \frac{v_i}{\sum_{k=1}^{n} v_k}, \quad i = 1, 2, \cdots, n \qquad (6)$$

where v is the eigenvector; v_i is the component of the i-th indicator; w_i is the normalized weight of the i-th indicator; k is the summation variable; and n is the number of indicators.

1.3.3 Linear weighted summation method

The comprehensive evaluation model is constructed using the linear weighted summation method. The weights of each indicator are combined with the sub-standardized scores to obtain the comprehensive desertification evaluation index, which is used to characterize the degree of desertification. The calculation formula is as follows:

Table 2 Indicator judgment matrix

Tab. 2 Indicator judgment matrix

Indicator	NDVI	NPP	Precipitation	Air temperature	Soil moisture	Soil organic matter	Population intensity
NDVI	1	1	2	3	2	4	5
NPP	1	1	2	3	2	4	5
Precipitation	1/2	1/2	1	2	1	3	4
Air temperature	1/3	1/3	1/2	1	1/2	3	4
Soil moisture	1/2	1/2	1	2	1	3	4
Soil organic matter	1/4	1/4	1/3	1/3	1/3	1	2
Population intensity	1/5	1/5	1/4	1/4	1/4	1/2	1

Note: The specific meanings of the numbers in the table are described in Section 1.3.2.

Table 3 Nine-point ratio scale

Tab. 3 Nine-point ratio scale

A indicator/B indicator	Extremely less important	Very less important	Less important	Slightly less important	Equal	Slightly more important	More important	Very important	Extremely important
Evaluation value	1/9	1/7	1/5	1/3	1	3	5	7	9

$$S = \sum_{i=1}^{n} (w_i \times x_i) \qquad (7)$$

where: S is the comprehensive desertification evaluation index; x_i is the sub-standard score corresponding to the i-th indicator.

1.3.4 Centroid migration model The desertification centroid is a geometric characterization of the balance of moments of specific desertification grades within the study area on the spatial plane, and its migration trajectory can quantitatively reflect the dynamic evolution characteristics of the spatial pattern of desertification [13]. By calculating the centroid coordinates of different desertification grades in different periods, this model analyzes the direction, path, and distance of migration, providing a visualized and quantitative tool for analyzing multi-scale spatiotemporal changes.

The formula for calculating centroid coordinates is as follows:

$$X_t = \frac{\sum_{i=1}^{q} C_{ti} X_i}{\sum_{i=1}^{q} C_{ti}}, \quad Y_t = \frac{\sum_{i=1}^{q} C_{ti} Y_i}{\sum_{i=1}^{q} C_{ti}} \qquad (8)$$

where: X_t and Y_t are the abscissa and ordinate, respectively, of the centroid of the t-th desertification grade; C_{ti} is the area of the i-th patch of the t-th desertification grade; (X_i, Y_i) is the geometric-center coordinate of that patch; q is the total number of patches of the t-th desertification grade; and t is the desertification grade.

2 Results and Analysis

2.1 Construction of the desertification evaluation indicator system and allocation of weights

Under the framework of triangular fuzzy numbers and the analytic hierarchy process, this study invited four experts in the field of desertification to make independent judgments on the importance of indicators. The nine-point proportional scale in Table 3 was used for pairwise comparisons, and a judgment matrix was constructed. A consistency test was performed on the matrix; if $CR < 0.1$, it was included in subsequent weight calculation. Finally, the weights of each indicator were determined according to expert scoring. Each indicator was graded using the natural-breaks method, and the experts assigned an importance score of 1–9 to each grade. The scoring results were then fuzzily synthesized using triangular fuzzy numbers to reduce uncertainty and obtain the final weighting results (Table 4).

The results show that, as a direct response indicator of whether land is desertified, the vegetation dimension accounts for 50.74% of the weight in the desertification evaluation process, among which NDVI and NPP account for 25.37% and 25.37%, respectively. The climate dimension, as a driving factor, accounts for 25.18%, with precipitation and temperature accounting for 14.94%

and 10.24%, respectively. The weights of the soil dimension and the human-activity dimension account for 20.38% and 3.72%, respectively; among them, soil organic matter and soil moisture, as response indicators

Table 4 Expert scoring and weighting results

Tab. 4 Expert scoring and weighting results

Indicator	Weight	Grading range	Score	Indicator	Weight	Grading range	Score
NDVI	0.2537	<0.13	1	Soil moisture	0.1494	<3.26	1
NDVI	0.2537	0.13~0.21	3	Soil moisture	0.1494	3.26~11.95	3
NDVI	0.2537	0.21~0.29	5	Soil moisture	0.1494	11.95~25.70	5
NDVI	0.2537	0.29~0.40	7	Soil moisture	0.1494	25.70~42.36	7
NDVI	0.2537	>0.40	9	Soil moisture	0.1494	>42.36	9
NPP	0.2537	<53.39	1	Soil organic matter	0.0544	<0.92	1
NPP	0.2537	53.39~175.00	3	Soil organic matter	0.0544	0.92~1.89	3
NPP	0.2537	175.00~302.55	5	Soil organic matter	0.0544	1.89~2.90	5
NPP	0.2537	302.55~438.99	7	Soil organic matter	0.0544	2.90~4.68	7

Indicator	Weight	Grading range	Score	Indicator	Weight	Grading range	Score
NPP	0.2537	>438.99	9	Soil organic matter	0.0544	>4.68	9
Precipitation	0.1494	<131.97	1	Population intensity	0.0372	<170	9
Precipitation	0.1494	131.97~238.75	3	Population intensity	0.0372	170~969	7
Precipitation	0.1494	238.75~345.52	5	Population intensity	0.0372	969~3444	5
Precipitation	0.1494	345.52~465.32	7	Population intensity	0.0372	3444~9393	3
Precipitation	0.1494	>465.32	9	Population intensity	0.0372	>9393	1
Temperature	0.1024	<−2.63	1				
Temperature	0.1024	−2.63~0.52	2				
Temperature	0.1024	0.52~3.75	6				
Temperature	0.1024	3.75~7.29	5				
Temperature	0.1024	>7.29	4				

with proportions of 5.44% and 14.94%, respectively; population intensity served as a driving factor, accounting for 3.72%.

2.2 Spatial distribution characteristics of desertification grades on the Mongolian Plateau

Using the natural breaks classification method in ArcGIS to classify the comprehensive desertification evaluation index, the degree of desertification on the Mongolian Plateau was divided into severely desertified grade areas, moderately desertified grade areas, lightly desertified grade areas, and non-desertified grade areas, and the classification thresholds determined for 2023 were fixed and applied to all other years. Taking 2023 as an example (Fig. 2), lightly and above desertified grade areas on the Mongolian Plateau accounted for approximately 83.4% of the total area, among which the severely desertified grade area had the highest proportion, at 41.9%, mainly located in the southwestern part of the Mongolian Plateau. The moderately desertified grade area accounted for 24.7%,

Fig. 2 Spatial distribution of desertification grades in the Mongolian Plateau in 2023

Figure 2: Fig. 2 Spatial distribution of desertification grades in the Mongolian Plateau in 2023

the lightly desertified grade area accounted for 16.8%, and the non-desertified grade area accounted for 16.6%. The non-desertified grade areas were mainly located in northern Mongolia and the northeastern part of Inner Mongolia Autonomous Region, China.

To further reveal the ecological-environmental differences among different desertification grade areas, the mean values of each indicator were statistically analyzed (Table 5). Overall, as the degree of desertification changed from severe to light and then to non-desertification, vegetation and moisture conditions showed a significant improving gradient: NDVI increased from 0.09 to 0.38; NPP increased from 31.55 g C·m^-2 to 439.83 g C·m^-2; precipitation increased from 90.97 mm to 425.95 mm; soil moisture and soil organic matter increased from 0.23 mm and 0.73% to 19.90 mm and 2.34%, respectively; meanwhile, air temperature decreased from 5.41 °C to 0.78 °C. Population intensity showed a non-monotonic change among different grades, with the highest value of 14.58 in lightly desertified grade areas and the lowest value of 1.92 in severely desertified grade areas, suggesting that human activities may have local effects, but overall vegetation–water–heat–soil conditions changed consistently along the gradient.

Fig. 2 Spatial distribution of desertification grades in the Mongolian Plateau in 2023

2.3 Spatiotemporal pattern and evolution of desertification on the Mongolian Plateau

Over the past 23 a, desertification grade areas on the Mongolian Plateau have been mainly concentrated in the southwest, whereas non-desertified grade areas have been mainly concentrated in the north and northeast (Fig. 3). From 2001 to 2005, the degree of desertification on the Mongolian Plateau showed a worsening trend, and severely desertified grade areas expanded toward the hinterland. From 2005 to 2015, the area of severely desertified grade areas showed a decreasing trend, the area of moderately desertified grade areas remained basically unchanged, and the areas of lightly desertified and non-desertified grade areas showed increasing trends. From 2015 to 2020, the overall degree of severe desertification on the Mongolian Plateau increased slightly, but severe desertification in the Inner Mongolia Autonomous Region of China decreased. From 2020 to 2023, the degree of desertification on the Mongolian Plateau worsened again; the area of non-desertified grade areas remained basically unchanged, while the area of severely desertified grade areas increased.

Desertification on the Mongolian Plateau exhibited staged changes from 2001 to 2023 (Fig. 4). From 2001 to 2005, the areas of severely and non-desertified grade areas increased by 2.9% and 2.0%, respectively, while the areas of moderately and lightly desertified grade areas decreased by 3.8% and 1.0%, respectively. From 2005 to 2015, the area of severely desertified grade areas decreased by 5.9%, the area of moderately desertified grade areas remained basically unchanged, and the areas of lightly and non-desertified grade areas increased by 3.6% and 1.7%, respectively. From 2015 to 2020, the areas of severely, lightly, and non-desertified grade areas increased by 1.5%, 2.2%, and 2.2%, respectively, while the area of moderately desertified grade areas decreased by 6.0%. From 2020 to 2023, the areas of severely and moderately desertified grade areas increased by 4.5% and 1.9%, respectively; the area of lightly desertified grade areas decreased by 6.3%, while the area of non-desertified grade areas remained basically unchanged.

The analysis results based on the gravity-center migration model indicate that, from 2001 to 2023, the gravity centers of the different desertification grade areas on the Mongolian Plateau showed clear migration trajectories in space (Fig. 5). The gravity-center locations of the severely and moderately desertified grade areas were close to each other. From 2001 to 2005, the gravity center of severely desertified areas migrated southeastward; from 2005 to 2010, it migrated northeastward; from 2010 to 2020, it migrated westward; and from 2020 to 2023, it migrated eastward.

Table 5 Statistics of the mean values of each indicator across different desertification grades in the Mongolian Plateau

Desertification grade	NDVI	NPP / g C · m^-2	Precipitation / mm	Air temperature / °C	Soil moisture / mm	Soil organic matter / %	Population intensity
Severe desertification	0.09	31.55	90.97	5.41	0.23	0.73	1.92
Moderate desertification	0.17	192.76	212.12	2.11	1.24	1.24	8.96
Light desertification	0.25	293.73	309.97	2.01	5.13	1.89	14.58
Non-desertification	0.38	439.83	425.95	0.78	19.90	2.34	7.93

(a) 2001

Legend
Desertification grade
Severe desertification
Moderate desertification
Mild desertification
Non-desertification

—National boundary
Mongolian Plateau

0 500 km

(b) 2005

Legend
Desertification grade
Severe desertification
Moderate desertification
Mild desertification
Non-desertification

—National boundary
Mongolian Plateau

0 500 km

(c) 2010

Legend
Desertification grade
Severe desertification
Moderate desertification
Mild desertification
Non-desertification

—National boundary
Mongolian Plateau

0 500 km

(d) 2015

Legend
Desertification grade
Severe desertification
Moderate desertification
Mild desertification
Non-desertification

—National boundary
Mongolian Plateau

0 500 km

(e) 2020

Legend
Desertification grade
Severe desertification
Moderate desertification
Mild desertification
Non-desertification

—National boundary
Mongolian Plateau

0 500 km

(f) 2023

Legend
Desertification grade
Severe desertification
Moderate desertification
Mild desertification
Non-desertification

—National boundary
Mongolian Plateau

0 500 km

Fig. 3 Distributions of different desertification grades in the Mongolian Plateau from 2001 to 2023

It migrated northward; the moderate desertification grade area, as a transition zone between severe and mild desertification, showed changes in the migration direction of its centroid in each period. The centroids of the mild and non-desertification grade areas had similar migration trajectories in some periods: from 2001 to 2010 they migrated westward and southeastward, respectively; from 2010 to 2015 both migrated southeastward; from 2015 to 2020 both migrated northwestward; and from 2020 to 2023 they migrated southeastward and northeastward, respectively.

3 Discussion

3.1 Weights of the desertification evaluation indicators and their effects

The weight results determined by the analytic hierarchy process show that the vegetation dimension had a weight of 50.74% in the desertification evaluation process, of which NDVI and NPP accounted for 25.37% and 25.37%, respectively. NDVI is used to characterize vegetation coverage and growth status, and NPP reflects vegetation productivity; both can directly reflect the degree of desertification and are important response indicators[^14].

The weight of the climate dimension was 25.18%, with precipitation and air temperature accounting for 14.94% and 10.24%, respectively. Precipitation is the most important source of water on the Mongolian Plateau; its changes directly affect soil moisture and vegetation growth and have a significant influence on the desertification process[^15-^17]. Rising air temperature, by enhancing evaporation and drought processes, intensifies soil-water loss and land degradation[^18]. Therefore, precipitation and air temperature are the main driving factors in the evaluation of desertification on the Mongolian Plateau.

In the soil dimension, the weights of soil moisture and soil organic matter were 14.94% and 5.44%, respectively. Soil moisture is a key resource for vegetation growth; precipitation, irrigation water, and groundwater can be converted into soil moisture before being absorbed and utilized by vegetation[^19]. Soil desertification is closely related to soil moisture[^20]. Water-stress experiments have shown that reduced soil moisture leads to soil drying, weakens soil fertility and structure, and insufficient soil moisture inhibits vegetation growth[^21]. Soil organic matter is an important indicator reflecting soil fertility; its reduction lowers the soil nutrient-supply capacity and increases

(a) 2001–2005

(b) 2005–2010

(c) 2010–2015

(d) 2015–2020

(e) 2020–2023

Desertification grade

- Severe desertification
- Moderate desertification
- Light desertification
- Non-desertification

Fig. 4 Trends in area changes across different desertification grades in the Mongolian Plateau from 2001 to 2023

Legend

Boundary line

Direction of center-of-gravity migration for desertification grades

- Severe desertification
- Moderate desertification
- Light desertification
- Non-desertification

Years: 2001, 2005, 2010, 2015, 2020, 2023

Mongolia

Inner Mongolia Autonomous Region, China

0 250 km

N

Fig. 5 Migration trajectories of the centers of gravity of areas with different desertification grades in the Mongolian Plateau from 2001 to 2023

increasing the risk of wind erosion and aggravating land degradation. In the evaluation of desertification on the Mongolian Plateau, soil moisture and soil organic matter, as important auxiliary indicators, can reflect regional soil conditions and ecological functions, and indirectly support the assessment of the degree of desertification[^22].

In comparison, the weight of the human-activity dimension is relatively low, with the population-intensity weight being only 3.72%. This may be because population distribution is relatively sparse in the Mongolian Plateau[^23], especially in areas where desertification is relatively severe, where population density is lower. The impacts of human activities may be very significant in local areas; for example, in areas with excessive grazing and concentrated exploitation of mineral resources, human production and living activities can lead to vegetation destruction, deterioration of soil structure, and shortages of water resources, thereby intensifying the process of desertification.

This paper constructs a comprehensive desertification evaluation index, reveals the spatial distribution pattern of desertification on the Mongolian Plateau, and, on this basis, uses contribution-rate analysis to quantify the relative importance of each driving factor. The contribution-rate 基

The proportion of each factor’ s weighted score in the total weighted score was calculated, and the robustness of the results was tested by Bootstrap resampling ($n = 1000$). The results show that the contribution rates of the factors were: NPP (29.60%), NDVI (24.32%), precipitation (15.23%), temperature (12.11%), population intensity (8.60%), soil moisture (5.85%), and soil organic matter (4.29%). Statistical tests indicate that the 95% confidence intervals of the contribution rates of all factors did not include zero, and the interval widths were all less than 0.3%, demonstrating that the results were statistically significant and highly robust. This analysis deepens the understanding of the formation process of desertification on the Mongolian Plateau from the perspective of driving mechanisms, and also provides a quantitative basis for regional prevention and control.

3.2 Differences in Desertification Change Between Mongolia and Inner Mongolia, China

Analysis of desertification evolution on the Mongolian Plateau over the past 23 years shows that desertification on the Mongolian Plateau has generally exhibited an improving trend (Fig. 6). Based on fixed classification thresholds, the desertification comprehensive index was classified into four grades: severe, moderate, light, and non-desertified. On this basis, the classification grids of two adjacent periods were subjected to pixel-level differencing, and the magnitude of grade change was classified into five evolution types: "significant increase, slight increase, unchanged, slight decrease, and significant decrease." During 2001–2005, the desertification degree of both Mongolia and Inner Mongolia Autonomous Region of China was worsening, which is also consistent with previous studies[24-25]. During 2005–2020, Inner Mongolia Autonomous Region of China entered a state of comprehensive recovery, and desertification gradually began to improve. During 2020–2023, due to the influence of precipitation, the area of severe desertification grades in Inner Mongolia Autonomous Region of China increased slightly, the area of light desertification grades decreased, and the areas of moderate and non-desertified grades remained basically unchanged. In Mongolia, after improvement in desertification during 2005–2015, the area of severe desertification grades began to increase rapidly during 2015–2023. Overall, since 2001, the desertification degree of Inner Mongolia Autonomous Region of China has improved, whereas that of Mongolia has worsened.

Climate change is an important driving factor in desertification evolution[26]. From 2001 to 2023, temperature on the Mongolian Plateau generally showed an upward trend, with an average annual warming rate of approximately 0.03 °C · a^{-1} and a maximum warming rate of 0.05 °C · a^{-1} (Fig. 7). Warming, on the one hand, enhances potential evaporation and atmospheric drought demand

(a) 2001–2005

(b) 2005–2010

(c) 2010–2015

(d) 2015–2020

(e) 2020–2023

Legend
National boundary
Mongolian Plateau

Trend of change in desertification grade
Significant increase
Slight increase
Unchanged
Slight decrease
Significant decrease

0 500 km

Fig. 6 Desertification change trends in the Mongolian Plateau from 2001 to 2023

(a) Air temperature change

Legend
–National boundary
Mongolian Plateau
Air temperature/°C
0.05
0.00

(b) Precipitation change

Legend
–National boundary
Mongolian Plateau
Precipitation/mm
8.94
–4.20

Fig. 7 Trends in air temperature and precipitation amount in the Mongolian Plateau from 2001 to 2023

Under conditions of insufficient precipitation, soil moisture deficits readily occur, inhibiting vegetation growth, causing decreases in NDVI and NPP and weakening the sand-fixing capacity of the land surface. On the other hand, reduced vegetation cover increases bare-ground area and raises the risks of wind erosion and soil degradation, forming a positive feedback process of "drought-vegetation degradation-enhanced erosion," thereby promoting the development of desertification.

Compared with warming, changes in precipitation more directly determine water availability in arid and semi-arid regions and are a key limiting factor affecting vegetation restoration and desertification mitigation. Since 2001, precipitation in the northern and northeastern Mongolian Plateau has generally shown an increasing trend, whereas the western and southwestern parts have shown a decreasing trend (Fig. 7), consistent with the regional differentiation of the spatial pattern of desertification. Increased precipitation can raise soil water content and prolong effective water supply during the growing season, promoting the recovery of grassland productivity and enhancing the surface' s resistance to wind erosion, thereby alleviating desertification; reduced precipitation, by contrast, intensifies water stress and, together with enhanced evaporation due to rising temperatures, causes vegetation degradation and soil water loss to proceed simultaneously, making desertification more likely to worsen.

The different grazing policies of Mongolia and China' s Inner Mongolia Autonomous Region are also among the important reasons for differences in desertification[^27]. Overgrazing reduces biomass and vegetation cover, weakens the soil-binding effect of litter and root systems, and increases surface exposure and sensitivity to wind erosion, thereby driving grassland degradation. The sharp increase in Mongolia' s total livestock numbers and the imbalance in herd structure have aggravated grassland degradation and land desertification. In China' s Inner Mongolia Autonomous Region, the grazing enclosure and rotational grazing policies have effectively reduced grassland ecological pressure[^28]. At the same time, a series of large-scale ecological restoration projects implemented by China have also effectively halted the expansion of desertification[^29-31]. Desertification control in Mongolia started relatively late and is also constrained by funding and technology, so ecological restoration has proceeded relatively slowly[^32].

4 Conclusion

(1) Vegetation occupies a dominant position in the comprehensive evaluation of desertification in the Mongolian Plateau and is the most direct ecological response indicator reflecting the degree of desertification. As the main driving factor, climate indicators affect the desertification process by regulating water and heat conditions. Soil indicators and population intensity play a supplementary role in desertification identification at the local scale.

(2) Areas of slight and higher desertification grades in the Mongolian Plateau account for a relatively large share. Severely desertified areas are concentrated in the southwestern Gobi region, where precipitation is scarce and vegetation is sparse. Slightly desertified and non-desertified areas are mainly distributed in the northeastern region, where moisture conditions are relatively favorable and vegetation cover is high.

(3) Over the past 23 years, desertification in the Mongolian Plateau has shown phased changes: from 2001 to 2005 the overall degree of desertification intensified; from 2005 to 2020 it showed a sustained improvement; and from 2020 to 2023, under the influence of factors such as climatic fluctuations, desertification rebounded somewhat. Desertification in China's Inner Mongolia Autonomous Region generally showed an improving trend, whereas desertification in Mongolia showed an aggravating trend. This difference may be related to the ecological protection policies, grassland management systems, and implementation intensity of ecological restoration projects in the two countries.

(4) Precipitation is the most important driving factor affecting the evolution of desertification in the Mongolian Plateau. Rising air temperature indirectly promotes land desertification by intensifying evaporation, while human activities have significant impacts in local areas, such as overgrazed areas.

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Comprehensive evaluation of desertification in the Mongolian Plateau based on a multi-factor linear model

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Abstract: Desertification is a widespread ecological and environmental issue in arid and semiarid regions. As an inland plateau located within a typical arid and semiarid climatic zone, the Mongolian Plateau faces severe desertification challenges that profoundly impact regional ecological security and sustainable socio-economic development. Based on four dimensions—vegetation, climate, soil, and human activities—this study selected seven indicators: The normalized difference vegetation index, net primary productivity, precipitation, temperature, soil moisture, soil organic matter, and population density. The triangular fuzzy number theory and the analytical hierarchy process were employed to determine indicator weights and establish a multifactor linear evaluation model. Combined with GIS technology, this model was used to conduct a comprehensive assessment of desertification across the Mongolian Plateau. The results indicate that: (1) The vegetation dimension holds the highest weight in the comprehensive evaluation (50.74%), making it the most direct indicator of desertification status. The climate dimension ranks second (25.18%), primarily reflecting the influence of precipitation and temperature on ecosystem processes. The soil and human activity dimensions account for 20.38% and 3.72%, respectively. (2) Areas classified as experiencing light, moderate, or severe desertification are mainly concentrated in the southwestern Mongolian Plateau and collectively account for ~83.4% of the total area. Specifically, severe, moderate, and light desertification cover 41.9%, 24.7%, and 16.8% of the total area, respectively. Nondesertified areas are primarily distributed in the northern and northeastern regions, accounting for 16.6% of the total area. (3) Desertification on the Mongolian Plateau showed an overall worsening trend from 2001 to 2005, followed by a period of improvement from 2005 to 2020 and a slight deterioration from 2020 to 2023. (4) Precipitation is the most crucial driving factor influencing the evolution of desertification in the Mongolian Plateau. Rising temperatures indirectly promote desertification by intensifying evaporation and drought conditions, while human activities exert significant localized impacts. (5) Regional comparisons reveal that desertification in Inner Mongolia has generally improved since 2001, whereas Mongolia has experienced a worsening trend. These contrasting patterns are associated with differences in ecological restoration policies and engineering measures implemented in the two regions.

Keywords: Mongolian Plateau; desertification; climate change; multi-factor linear model; spatiotemporal process

Note: Figure translations are in progress. See original paper for figures.