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Assessment of Land Degradation at the Local Level in Response to SDG 15.3: A Case Study of the Inner Mongolia Region from 2000 to 2020

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Abstract: SDG15.3 aims to achieve "Land Degradation Neutrality (LDN)", but its only indicator (SDG15.3.1) is designed for national-level assessment and monitoring, and is not suitable for local-level applications. Thus, taking Inner Mongolia as the study area, this paper provides a localized reform of SDG15.3.1 based on the local context, and assesses the progress of SDG15.3 in the study area (2000-2020) at multiple levels (indicator, specific, and overall). The Moran'I and Standard Deviation Ellipse (SDE) are also utilized to analyze the spatial–temporal change of land degradation. The results show that as of 2020, the proportion of land degradation and improvement areas to the total area was 7.51% and 9.42%, respectively. Inner Mongolia had generally met the goal of SDG15.3, but on the indicator level, water erosion still falls far below the standard of SDG15.3. Additionally, at the spatial level, 3 out of 12 municipalities and 71 out of 103 counties had not achieved LDN, with a pattern of low LDN levels in the southeast and high in the northwest at the county scale. This indicates that the progress of SDG15.3 is extremely uneven both at the indicator and spatial levels. Thus, it is essential to continue to promote land degradation management in Inner Mongolia to achieve LDN in the entire area and across all aspects.

Keywords: sustainable development goal 15.3; land degradation neutrality (LDN); local level; localized assessment; spatial–temporal distribution

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Citation: Li, Z.; Wang, Y.; Dong, J.; Luo, X.; Wu, H.; Wan, Y. Assessment of Land Degradation at the Local Level in Response to SDG 15.3: A Case Study of the Inner Mongolia Region from 2000 to 2020. *Sustainability* **2023**, *15*, 4392. https://doi.org/10.3390/su15054392

Academic Editor: Fernando António Leal Pacheco

Received: 24 January 2023
Revised: 20 February 2023
Accepted: 21 February 2023
Published: 1 March 2023

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1. Introduction

In September 2015, the UN Sustainable Development Summit adopted the 2030 Agenda for Sustainable Development, which set out 17 sustainable development goals (SDGs). Among them, SDG15.3 focuses on the sustainability of land resources and aims to achieve "Land Degradation Neutrality", with "the proportion of land that is degraded over total land area" (SDG15.3.1) as the only assessment indicator [1]. Land degradation is defined as "the reduction or loss of the biological or economic productivity and complexity of rain-fed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from a combination of pressures, including land use and management practices" [2]. As the core requirement and concrete embodiment of SDG15.3 [3] LDN refers to "a state whereby the amount and quality of land resources, necessary to support ecosystem functions and services and enhance food security, remains stable or increases within specified temporal and spatial scales and ecosystems", which is essentially a balance between land degradation and improvement [2,4]. In reality, despite research results by Guo et al. indicating that the overall global land restoration area is greater than the land degradation area, the problem of land degradation remains persistent [5]. A total of 20% of the world's total land area experienced degradation from 2000 to 2015, affecting the lives of more than one billion people directly. Currently, land degradation causes habitat loss and habitat suitability decline, which contributes to the economic cost of loss exceeding 10% of the world's annual

gross domestic product [6]. Therefore, scientifically and accurately assessing the progress of SDG15.3, effectively reducing land degradation, and restoring the degraded land are important challenges that must be addressed on the road to the sustainable development of human beings [7,8].

Due to the harmful effects of land degradation, many scholars around the world conducted a lot of research on its monitoring and assessment. In the 1990s, soil degradation was the focus of research [9]. The degradation degree and causes (e.g., water, wind, salt, nutrient depletion, etc.) were determined based on expert experience, but there was no consistent standard to measure them. With the continuous development of GIS technology, the methods to assess land degradation gradually changed from subjective and qualitative to objective and quantitative [10,11]. In some studies, land cover changes were used for identifying land degradation [12–14], but this method was invalid when land degradation occurred without land cover change. Therefore, some scholars proposed to detect changes in land productivity through a long-term vegetation index, such as NDVI and NPP, which laterally reflect land degradation [15–19]. However, in terms of SDGs, land degradation includes negative changes in multiple dimensions such as vegetation, soil, utilization patterns, etc. The vegetation index only focuses on the perspective of plant productivity, which cannot provide a complete description of land resources and accurately identify the key factors causing land degradation, so it is difficult to be directly applied in the study of SDG15.3 monitoring and assessment.

Given the above problems, the Inter-Agency and Expert Group on SDGs (IAEG-SDGs) proposed SDG15.3.1 as the only indicator for SDG15.3 and identified land productivity (measured by NPP), land cover, and soil organic carbon (SOC) together as the land degradation identification indicators. On this basis, the United Nations Convention to Combat Desertification (UNCCD) explained the data sources and calculation methods of the above indicators in the Good Practice Guidance (GPG) for SDG 15.3.1 to ensure strong operability [2]. However, as the ultimate goal of SDG 15.3, LDN aims to achieve a balance of degradation and improvement. SDG15.3.1, which only focuses on degradation without improvement, is not comprehensive and cannot accurately reflect the progress of SDG15.3. Therefore, a new indicator reflecting the core requirements of SDG 15.3 should be established to complete SDG 15.3.1.

In addition, the land degradation assessment system in GPG is designed for a global scale and is mainly conducted for the assessment of SDG15.3 at the national or regional level [3,20–22]. In practice, due to the diversity and regional heterogeneity of land degradation, the realization of SDG15.3 requires targeted actions by decision-makers at all levels, especially local governments. Therefore, the assessment of SDG15.3 should focus on the local level (provincial, municipal, county, etc.) so that the government actions taken can be adapted to local conditions. However, the complexity of land degradation leads to differences or even conflicts in the identification indicators and criteria in different regions [23], which makes it difficult to directly apply the above indicator system to regions in different natural conditions, human conditions, and development stages. Therefore, undertaking the localization reform of the original indicator system to establish a localized indicator system that accurately reflects local land degradation and improvement is necessary.

In recent years, the Chinese government has placed great emphasis on promoting the SDGs process and has made progress in managing land degradation, but the problem remains serious in some regions [24,25]. Due to severe soil erosion and sandstorms, Inner Mongolia is one of the regions in China with the most severe land degradation. As a result of projects like the Three-North Shelterbelt Project and the Grain for Green Project, the vegetation cover in the desert and surrounding areas has increased. Currently, the land degradation in the priority control areas has been largely curtailed, and in some areas, it has even reversed. Therefore, an assessment of land degradation in Inner Mongolia towards SDG15.3 will help reveal the achievements and shortcomings of local management actions. This is extremely necessary for the formulation of more scientific policies to support the implementation of SDG15.3.

Against this background, aiming at the 2030 Agenda for Sustainable Development, this paper proposes to construct a local-level localized assessment system for SDG15.3 with Inner Mongolia Autonomous Region as the study area. It first defines localized assessment indicators and criteria based on the natural conditions and policy characteristics of the research area to quantitatively assesses the degree of land degradation and improvement during 2000–2020 at the local level. On this basis, this paper uses Moran's I and SDE methods to reveal the spatial-temporal patterns of land degradation, and proposes a LDN quantification method to further reveal the gap between the current land degradation status and the requirements of SDG15.3. Finally, it provides support for local governance policies in a timely and local context.

2. Materials and Methods

2.1. Study Area

Inner Mongolia Autonomous Region (37°24′–53°23′ N, 97°12′–126°04′ E) is located in the north of China, with the terrain extending diagonally from northeast to southwest across Northeast China, North China, and Northwest China. The region covers an area of 1.183 million km^2, with jurisdiction over 12 prefecture-level divisions and 103 county-level divisions. The climate of this region is mainly temperate continental climate, with obvious spatial differentiation: In the eastern region, concentrated and heavy rainfall results in serious hydraulic erosion in the low mountains and hills with poor vegetation. In the western region, the arid climate, sparse vegetation, and frequent high winds lead to severe wind erosion [26,27] (Figure 1).

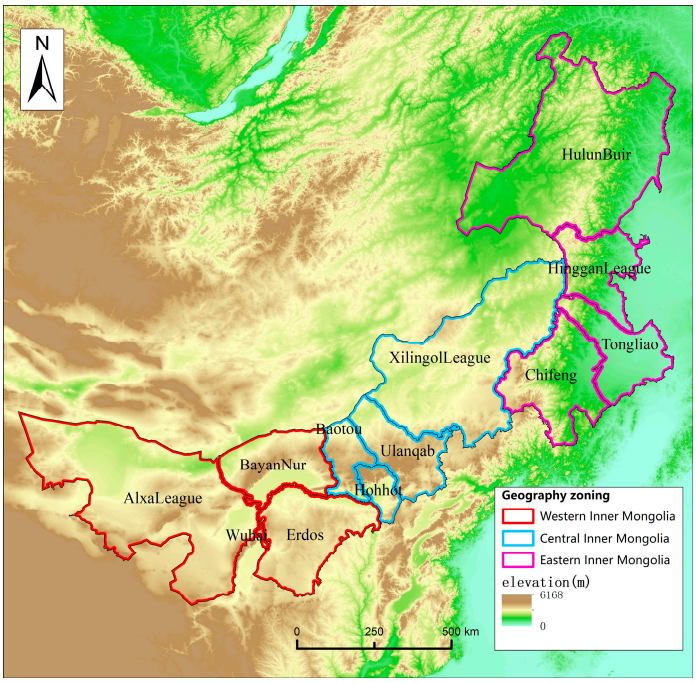


Figure 1. An overview of the study area.

The region is an important agricultural and animal husbandry base in China, with a grain sown area of 6.88 million hectares and a total output of 7.68 billion kg, ranking sixth in the country in 2020 [28]. It also has the largest grassland grazing area in China, an important supply base for livestock products [29]. However, due to the long-term influence of unreasonable human activities such as overgrazing and grassland reclamation, coupled with its special climatic, topographical, and geomorphological conditions, the region has serious land degradation problems, which hinders sustainable development and healthy development of its natural and economy [30].

2.2. Data and Preprocessing

2.2.1. Basic Data

The basic data includes NPP and EVI data (2000 to 2020), land cover, meteorological data, and soil data (2000, 2005, 2010, 2015, and 2020), which are listed in Table 1. These data were preprocessed with coordinate system conversion, geographic alignment, and data linkage, and resampled to 500 m resolution. To verify the impact of resampling on the results, the Fractional Vegetation Cover (FVC) was calculated using both the original 250 m resolution EVI data and the resampled 500 m resolution EVI data. On this basis, the sustainable development level of this indicator was assessed at the provincial, municipal, and county levels. The differences between the results obtained from these two methods were analyzed, and the results show that at the provincial scale, the Root Mean Squared Error (RMSE) was 0 and the R^2 was 1; at the municipal scale, the RMSE was 0.001 and the R^2 was 0.979; at the county scale, the RMSE was 0.002 and the R^2 was 0.966. This indicates that the impact of resampling on the experimental results is minimal and that the resampled data can be used in the assessment of SDG15.3.

Table 1. Data for land degradation assessment.

Data	Resolution	Data Source	Collected Date
Land cover	500 m	MODIS product (MCD12Q1) https://modis.gsfc.nasa.gov/data/dataprod/mod12.php (accessed on 4 July 2022)	4 July 2022
NPP	500 m	MODIS product (MOD17A3HG) https://lpdaac.usgs.gov/products/mod17a3hgfv006/ (accessed on 11 May 2022)	11 May 2022
EVI	250 m	MODIS product (MOD13Q1) https://lpdaac.usgs.gov/products/mod13q1v006/ (accessed on 5 July 2022)	5 July 2022
Snow depth	0.25°	Long-term series of daily snow depth dataset in China (1979–2021), Cold and Arid Regions Sciences Data Center at Lanzhou (http://westdc.westgis.ac.cn) (accessed on 16 June 2022)	16 June 2022
Climate	-	China National Climate Center http://data.cma.cn/ (accessed on 2 June 2022)	2 June 2022
Soil properties	1000 m	Harmonized World Soil Database v 1.2 https://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en (accessed on 14 June 2022)	14 June 2022

2.2.2. Soil Data Estimation

The public soil dataset has outdated data and lacks long time series data, while field measurements are labor-intensive and difficult to apply on a provincial level, and cannot meet the monitoring needs of SDG15.3. Therefore, this paper estimates the stocks of *SOC* and the intensity of soil erosion (wind and water erosion) in 2000, 2005, 2010, 2015, and 2020 using the following methods, with a spatial resolution of 500m for the estimation results.

1. Estimation of *SOC* stocks

This paper utilizes the method provided by the UNCCD [2] to estimate *SOC* stocks at a pixel level of the study area. This method draws on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, which is highly scientific and feasible. The calculation method is as follows:

$$\Delta SOC = \frac{SOC_0 \times F_{LU} \times F_{MG} \times F_I - SOC_0}{D} \quad (1)$$

$$SOC_T = \Delta SOC \times T + SOC_0 \quad (2)$$

where: ΔSOC represents the annual change in *SOC* stock in the grid cell, $g \cdot kg^{-1} \cdot yr^{-1}$; SOC_0 represents *SOC* stock at the beginning of the reporting period, $k \cdot kg^{-1}$; SOC_T represents

SOC stock in the last year of a reporting period ($k \cdot kg^{-1}$); *D* represents the default period for transition between equilibrium *SOC* values, commonly 20 years, yr; F_{LU}, F_{MG}, and F_I represent stock change factor for land-use systems, management regime, and the input of organic matter, dimensionless, respectively; T represents the number of years over a reporting period, yr.

2. Estimation of wind erosion

The estimation method of wind erosion is the Revised Wind Erosion Equation (RWEQ). REWQ developed by the United States Department of Agriculture (USDA), is an empirical model based on process simulation that integrates climate, soil, vegetation, and other factors, and is widely used in the study of wind erosion, windbreak, and sand fixation in Inner Mongolia [27,31,32], which proves its applicability to the study area. Therefore, this paper utilizes RWEQ to estimate wind erosion at a pixel level in the study area. The calculation method is as follows:

$$Q_{max} = 109.8 \times (WF \times EF \times SCF \times K \times C) \quad (3)$$

$$S = 150.71 \times (WF \times EF \times SCF \times K \times C)^{-0.3711} \quad (4)$$

$$S_L = \frac{2x}{S^2} Q_{max} e^{-(\frac{x}{S})^2} \quad (5)$$

where S_L represents the annual wind erosion, $t \cdot hm^{-2} \cdot yr^{-1}$; *S* represents the critical plot length, m; Q_{max} represents the maximum sediment transport capacity, $kg \cdot m^{-1}$; x represents the calculated downwind distance, m; *WF* represents weather factor, $kg \cdot m^{-1}$; EF represents soil erodibility fraction, %; *SCF*, *K*, and *C* represent soil crust factor, soil roughness factor, and vegetation factor, respectively, dimensionless.

3. Estimation of water erosion

The estimation method of water erosion is the Revised Universal Soil Loss Equation (RUSLE). RUSLE is a modified version of the Universal Soil Loss Equation (USLE) proposed by the USDA, which simulates soil erosion based on precipitation, topography, soil, and vegetation-management factors, and is widely used at various scales such as provincial, municipal, county, and watershed in China [33–35]. Therefore, this paper utilizes RWEQ to estimate water erosion at a pixel level in study area. The calculation method is as follows:

$$A = R \times K' \times LS \times C' \times P \quad (6)$$

where *A* represents the annual water erosion, $t \cdot hm^{-2} \cdot yr^{-1}$; *R* represents fall erosion factor, $MJ \cdot mm \cdot hm^{-2} \cdot h^{-1} \cdot a^{-1}$; *K′* represents soil erodibility fraction, $t \cdot hm^2 \cdot h \cdot MJ^{-1} \cdot mm^{-1} \cdot hm^{-2}$; *LS* represents terrain factor, dimensionless; *C′* represents vegetation factor, dimensionless; *P* represents management factor, dimensionless.

2.3. Methods

SDG15.3.1 is designed to reflect the extent of land degradation, which is just one aspect of the content of SDG15.3. Compared to it, LDN, which is the core requirement of SDG15.3, is undoubtedly more suitable as an evaluation indicator for SDG15.3. LDN refers to the balance between the "losses" to land degradation and "gains" to land improvement in land resources. It is worth noting that "losses" and "gains" in LDN do not only refer to the area, otherwise there is a risk that losses involving very severe degradation may be counteracted by a small gain on an equal area [2,4]. Therefore, the balance mechanism of LDN should consider not only the direction and area of land resource variation but also its degree, which means the assessment of LDN should be based on the quantitative assessment of the degree of land degradation and improvement. To SDG15.3, the original land degradation indicator system is designed for assessment and monitoring at the global and national levels, this leads to the issue of lacking localized indicators, assessment criteria, and quantitative assessment models when applying these indicators at the local level [36].

To address this, a localization reform must be carried out to enhance, expand, and adjust the original indicator system to fit the local context [37]. Subsequently, a quantitative assessment of land degradation and improvement is carried out based on this, and finally, the LDN is calculated using the evaluation results.

2.3.1. Define the Localized Indicators for SDG15.3

Given the serious desertification and soil erosion in Inner Mongolia, the Fractional vegetation cover (FVC), which is widely used in desertification assessment studies in China, is used as a localized indicator of land degradation. In the same vein, wind erosion and water erosion, as the predominant forms of soil erosion in Inner Mongolia, are also designated as local indicators of land degradation. In short, on the basis of the original indicators (NPP, land cover, and *SOC*), this paper supplements FVC, wind and water erosion as localized indicators, formulates land degradation criteria according to regional characteristics, and finally constructs a more comprehensive and representative localized indicator system to grasp the land degradation and improvement in Inner Mongolia and monitor the progress of SDG15.3. The indicators are calculated as follows:

1. *SOC* stocks, wind erosion, and water erosion

SOC stocks are an important factor in determining high and stable yields of cultivated land, as well as being essential for a variety of ecosystem services and an indication of the quality of the land [38]. Compared with other indicators, *SOC* stocks change slowly. To highlight the significance of change and reduce the uncertainty of the estimated result, the GPG recommends setting degradation thresholds. Degradation is only considered when *SOC* stocks reduce by more than 10% [2]. Adhering to this idea, this paper refines the thresholds according to the classification criterion of soil nutrients in the second national soil census in China [39] to make it more consistent with local characteristics. As shown in Table 2, among which soil organic matter (*SOM*) can be converted by *SOC* through the Van Bemmelen factor [40]. The calculation method is as follows:

$$SOM = SOC \times VBF \quad (7)$$

where *SOM* represents soil organic matter stocks, g/kg; *VBF* represents the Van Bemmelen factor, 1.724 here, dimensionless.

Table 2. Classification criterion of soil nutrient.

Soil Nutrient Levels	*SOM* Stocks (g/kg)	*SOC* Stocks Levels
1	>40	0
2	30–40	1
3	20–30	2
4	10–20	3
5	6–10	4
6	<6	5

The estimation result of soil erosion is affected by many factors, minor changes in climate, vegetation, and human activities can cause fluctuation in it, which cannot represent land degradation or improvement occurred. UNCCD also points out that an indicator is considered to have degraded or improved only if it exhibits a "significant" trend [4]. Therefore, this paper reflects the significance of soil erosion changes by setting thresholds, which draw on the standard for the classification and gradation of soil erosion in China [41]. As shown in Table 3, soil erosion levels are divided according to soil erosion modulus.

Table 3. The standard for classification and gradation of soil erosion.

Level	Water Erosion Modulus, $t \cdot km^{-2} \cdot a^{-1}$	Wind Erosion Modulus, $t \cdot km^{-2} \cdot a^{-1}$	Soil Erosion Level
1	<200	<200	0
2	200~2500	200~2500	1
3	2500~5000	2500~5000	2
4	5000~8000	5000~8000	3
5	8000~15,000	8000~15,000	4
6	>15,000	>15,000	5

On this basis, this study assigns values to the indicators based on the change in the degree of the change in the level of SOC, wind erosion, and water erosion. The calculation method is as follows:

$$Index = Level_T - Level_{T-1} \quad (8)$$

where *Index* represents the magnitude of changes in SOC/wind erosion/water erosion; $Level_{T-1}$ represents the indicator level at the beginning of the reporting period, dimensionless; $Level_T$ represents the indicator level in the last year of a reporting period, dimensionless. *Index* > 0 represents the degradation of the indicator; *Index* < 0 represents the improvement of the indicator; *Index* = 0 represents the indicator remains stable.

2. NPP and FVC

Due to the interannual change of climate conditions, NPP and FVC have high fluctuations in the time dimension. Therefore, relevant studies mostly conducted an analysis of land degradation from the perspective of changing trends in them. The GPG also recommends using Mann–Kendall to check the significance of the trend. In this paper, the Theil–Sen median combined with Mann–Kendall are used to calculate the trend of NPP and FVC, and determine the significance of the trend slope. Only the data that passed the significance test could be used to evaluate the degree of land degradation and improvement. The calculation method is as follows:

$$Index = indicator_0 - indicator_T \quad (9)$$

where *Index* represents the magnitude of changes in NPP/FVC; $indicator_0$ represents the value of NPP/FVC at the beginning of the reporting period; $indicator_T$ represents the value of NPP/FVC in the last year of a reporting period. *Index* > 0 represents the degradation of indicator; *Index* < 0 represents the improvement of indicator; *Index* = 0 represents the indicator that remains stable.

3. Land cover

Land cover refers to the observed (bio) physical cover on the Earth's surface, which is used to identify whether land degradation has occurred or not. It should be noted that the criteria for land degradation differ between regional contexts. In Inner Mongolia, efforts are being made to implement the reforestation policy, with a focus on enhancing the quality of the region's forest and grass resources, as well as on preserving wetlands and cultivated land. Based on the above conditions, a transition matrix is generated to specify land cover changes as degradation, improvement, or neutral transitions, and calculate the extent of the change. As shown in Table 4, the table provides the valuation method for land cover change, which is determined through the comparison of land cover types at the beginning and end of the reporting period. The Original Class represents the land cover at the beginning of the reporting period (2000, 2005, 2010, 2015), and the Final Class represents the land cover at the last year of the reporting period (2005, 2010, 2015, 2020).

Table 4. Transition matrix for land cover.

Land Cover		Final Class						
		Forest	**Grassland**	**Wetland**	**Cultivated Land**	**Bare Land**	**Artificial Surfaces**	**Water Bodies**
Original Class	Forest	0	0	0	−1	−2	−3	0
	Grassland	0	0	0	−1	−2	−3	0
	Wetland	0	0	0	−1	−2	−3	0
	Cultivated land	1	1	1	0	−1	−2	−3
	Bare land	2	2	2	1	0	−1	−2
	Artificial surfaces	3	3	3	2	1	0	−1
	Water bodies	0	0	0	0	0	0	0

The numbers in the table indicate the extent of the change in land cover, where a value =0 indicates a neutral transition, a value <0 indicates an improvement, and a value >0 indicates a degradation.

2.3.2. Standardization of Indicators

Using the range method to standardize each indicator with values ranging from −1 to 1, the calculation method is shown as follows:

$$SDV_{i,j} = \begin{cases} \left(\left|OV_{i,j}\right| - OV_{j,min}\right) / \left(OV_{j,max} - OV_{j,min}\right), OV_{i,j} \geq 0 \\ -\left(\left|OV_{i,j}\right| - OV_{j,min}\right) / \left(OV_{j,max} - OV_{j,min}\right), OV_{i,j} < 0 \end{cases} \quad (10)$$

where $SDV_{i,j}$ represents the standardized value of indicator j of land unit i; $OV_{i,j}$ represents the value of indicator j of land unit i; $OV_{j,max}$ and $OV_{j,min}$ represent the maximum and minimum absolute values of indicator j in all land units, respectively.

2.3.3. Assessment of Land Degradation and Improvement

1. Determination of indicators weights

In this paper, the entropy weight method (EWM) is used to determine the weight of indicators (Table 5). EWM depends on the information of the data itself and is not affected by the subjective consciousness of the people, so it can accurately reflect the characteristics of the data itself and has objectivity. The calculation method is as follows:

$$W_j = \frac{1 - E_j}{\left|6 - \sum_{j=1}^{6} E_j\right|}, E_j = \frac{-1}{\ln(n)} \left| \sum_{i=1}^{n} p_{i,j} \ln\left(p_{i,j}\right) \right| \quad (11)$$

where $p_{i,j} = SDV_{i,j} / \sum_{i=1}^{n} SDV_{i,j}$, E_j represents the information entropy of indicator j, W_j represents the entropy weight of indicator j.

2. Calculation of land degradation and improvement degree

Table 5. Results of the weights of each indicator determined by EWM.

Assessment Object	Indicator	Weight
The degree of land degradation and improvement	NPP	0.1489
	Land cover	0.0910
	FVC	0.1274
	Wind erosion	0.1488
	Water erosion	0.2774
	SOC	0.2066

According to the "ONE OUT ALL OUT" principle proposed in the GPG, if any of the six indicators experience a significant negative change (>0), the land unit is considered to be degraded; if there is no significant change (=0), the land unit is considered to be stable; otherwise, the land unit is considered to be improved. The calculation method is as follows:

$$De_{i,j} = \begin{cases} SDV_{i,j} & , SDV_{i,j} \geq 0 \\ 0 & , SDV_{i,j} < 0 \end{cases}, Re_{i,j} = \begin{cases} SDV_{i,j} & , SDV_{i,j} < 0 \\ 0 & , SDV_{i,j} \geq 0 \end{cases} \quad (12)$$

$$De_i = \sum_{j=1}^{6} \omega_j \times De_{i,j}, Re_i = \begin{cases} \sum_{j=1}^{6} \omega_j \times Re_{i,j} & , De_i \leq 0 \\ 0 & , De_i > 0 \end{cases} \quad (13)$$

where $De_{i,j}$ and $Re_{i,j}$ represents the degradation and improvement degree of indicator j of land unit i, respectively; $P_{i,j}$ represents the standardized value of indicator j of land unit i; De_i and Re_i represent the degradation and improvement degree of land unit i, respectively.

2.3.4. Assessment of LDN

Based on the connotation of LDN, this paper uses the gap between the losses of land resources lost due to degradation and the gains through improvement to evaluate LDN at both the individual indicator and overall levels across multiple scales (province, municipality, and county). If the losses ≥ gains, it is considered that LDN has been achieved in this region and SDG15.3 has been realized. To make comparisons more accurate, using a weighted area to represent the losses and gains of land resources based on the degree of degradation or improvement helps to comprehensively reflect the direction, area, and degree of land resource change. The calculation method is as follows:

$$LDN = (R - D)/(R + D) \quad (14)$$

$$D = \sum_{i=0}^{n} S_0 \times De_i, R = \sum_{i=0}^{n} S_0 \times Re_i \quad (15)$$

where LDN refers to the degree of land degradation neutrality in a specific region, which can be a province, municipality, or county; D refers to the losses of land resources in a region; R = the gains of land resources in a region; S_0 refers to the area of the land unit; De_i represents the degradation degree of land unit i; Re_i represents the improvement degree of land unit i; n represents the number of land units in the region. When $LDN > 0$, the region achieved land degradation neutrality, which is SDG15.3. The assessment of LDN at the indicator level is similar:

$$LDN_j = \left(R_j - D_j\right)/\left(R_j + D_j\right) \quad (16)$$

$$D_j = \sum_{i=0}^{n} S_0 \times De_{i,j}, R_j = \sum_{i=0}^{n} S_0 \times Re_{i,j} \quad (17)$$

where LDN_j represents the LDN degree of indicator j in a region; D_j and R_j represent the losses and gains caused by indicator j in a region, respectively; S_0 represents the area of the land unit; $De_{i,j}$ and $Re_{i,j}$ represents the degradation and improvement degree of indicator j in land unit i, respectively; n represents the number of land units. $LDN_j > 0$ represents the region that achieved land degradation neutrality at the indicator j level.

2.3.5. Spatial–Temporal Distribution Trend Analysis Method

1. Standard Deviational Ellipse

The standard deviational ellipse method (SDE) was first proposed by Lefever in 1926 [42], which can reveal the spatial distribution characteristics of various geographical features and has been widely used in many fields [43,44]. In this paper, the SDE method is used to reveal the spatial–temporal distribution pattern of land degradation with its parameters (center coordinates, rotation angle, major and minor axis standard deviations). Among them, the center coordinates reveal the gravity center of land degradation, which can describe its relative position; the major and minor axe standard deviations are used to measure the range of land degradation distribution, and the major axis can reflect the main distribution direction of land degradation; the rotation angle is the angle at which the major axis rotates clockwise from due north and reflects the main trend direction of land degradation [45].

2. Moran's I

Moran's I can reveal whether there is a significant spatial dependence of land degradation in the study area, and reflect its spatial distribution aggregation characteristics. The value of Moran's I ranges from [−1,1], the larger the value, the stronger the spatial dependence of land degradation. A value closer to 1 indicates a stronger spatial positive correlation; a value closer to −1 indicates a stronger spatial negative correlation; a value equal to 0 indicates that the spatial unit attributes are randomly distributed and there is no spatial autocorrelation [46].

3. Results

3.1. Land Degradation and Improvement in Study Area over the Last 20 Years

3.1.1. Land Degradation

According to the above methods, land degradation in the study area during 2000–2020 was assessed in five-year study periods: the first period (2000–2005), the second period (2005–2010), the third period (2010–2015), and the fourth period (2015–2020), respectively. In order to make the result more intuitive, the natural breaks classification method (NBC) was used to grade the degree of land degradation. By minimizing the intra-class variance and maximizing the inter-class variance, NBC can objectively reflect the data characteristics. Therefore, through NBC, the land degradation degree was classified into four levels: not degraded (=0), light degraded (0–0.061), moderate degraded (0.041–0.112) and strong degraded (>0.112). The results are shown in Figure 2, land degradation in Inner Mongolia was more severe in the east and south, while lighter in the west and north.

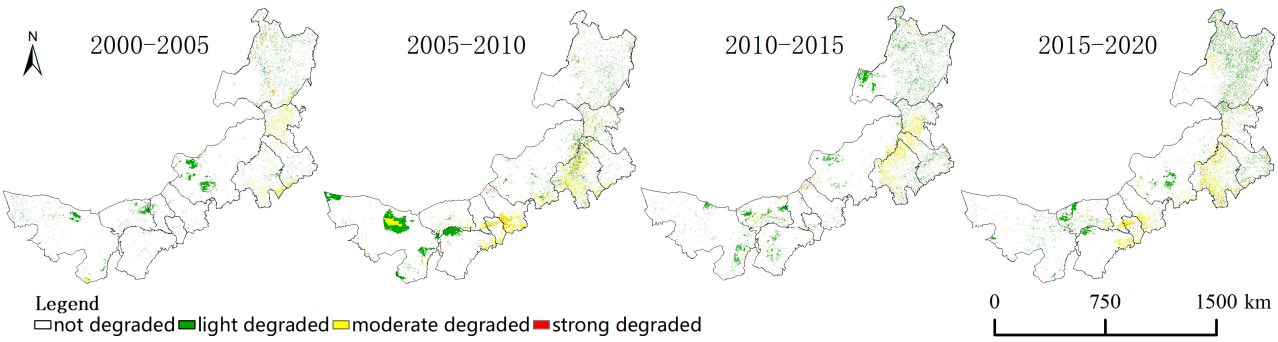


Figure 2. Land Degradation in study area.

In terms of degradation forms, as shown in Figures 3 and 4, the main land degradation forms in the study area were the negative changes of wind erosion and water erosion. Among them, wind erosion was mainly distributed in the central and western regions, with the highest proportion from 2000 to 2015. Due to the implementation of wind-prevention and sand-fixing projects, wind erosion was improved, and the proportion of wind erosion degradation area decreased significantly, while the proportion of water erosion increased, and became the main land degradation form in the fourth period, exceeding that of wind erosion. It can be seen that water erosion was mainly distributed in the southeastern edge of Inner Mongolia and tended to spread westward.

From the perspective of spatiotemporal changes, the land degradation situation in the study area was best in the first period, with its coverage area and degree much lower than the other three periods. Among them, the second period was the most serious due to the unreasonable development of land resources, with its coverage area increasing by 106.44% compared to the previous period. Subsequently, after taking positive governance measures, the land degradation coverage area in the third and fourth periods decreased by 18.61% and 11.25%, respectively. By 2020, 7.51% of the total area was occupied by land degradation. In terms of spatial distribution, as shown in Figure 5a, the land degradation in Inner Mongolia was distributed in the direction of "northeast–southwest" and moved to the southwest, indicating that the land degradation in the southwest was gradually

becoming more serious compared to that in the northeast. From the change of the long and short semiaxes, the short semiaxis decreased from 334.8 km to 303.7 km, indicating that the land degradation was shrinking in the direction of "northwest–southeast" and had a certain aggregation phenomenon. By 2010, the long semi-axis increased from 789.3 km to 845.6 km, indicating that the land degradation spread in the main direction during this period, while by 2020, the long semi-axis decreased to 784.2 km, indicating that the land degradation was shrinking in the "northeast–southwest" direction during this period. From a spatial correlation perspective, as shown in Figure 5b, Moran's I of land degradation increased from 0.361 to 0.497, and the Z-score was always higher than 1.96, with the *p*-value always lower than 0.05. This indicates that land degradation in Inner Mongolia had a significant positive spatial correlation and a certain aggregation effect, and the degree of aggregation increased. In addition, during the study period, most regions were located in the first and third quadrants. This indicates the pattern of land degradation aggregation primarily characterized by the pattern of land degradation aggregation in Inner Mongolia is mainly characterized by high–high degree degradation aggregation and low–low degree degradation aggregation.

3.1.2. Land Improvement

The degree of land improvement in Inner Mongolia was classified as stable (=0), light (0–0.045), moderate (0.045–0.085), and strong (>0.085) by NBC, and the results are shown in Figure 6. It can be seen that land resources were improved the most in the first period and were concentrated in the eastern region; however, in the second period, the coverage of improvement was reduced by 67.41%. Subsequently, due to the influence of ecological management actions such as grass–livestock balance and grazing bans, land resources in the study area were improved steadily. The coverage of improvement in the third and fourth periods increased by 33.67% and 5.75%, respectively, compared to the second period. By 2020, the area of land improvement accounted for 9.42% of the total area in the study area.

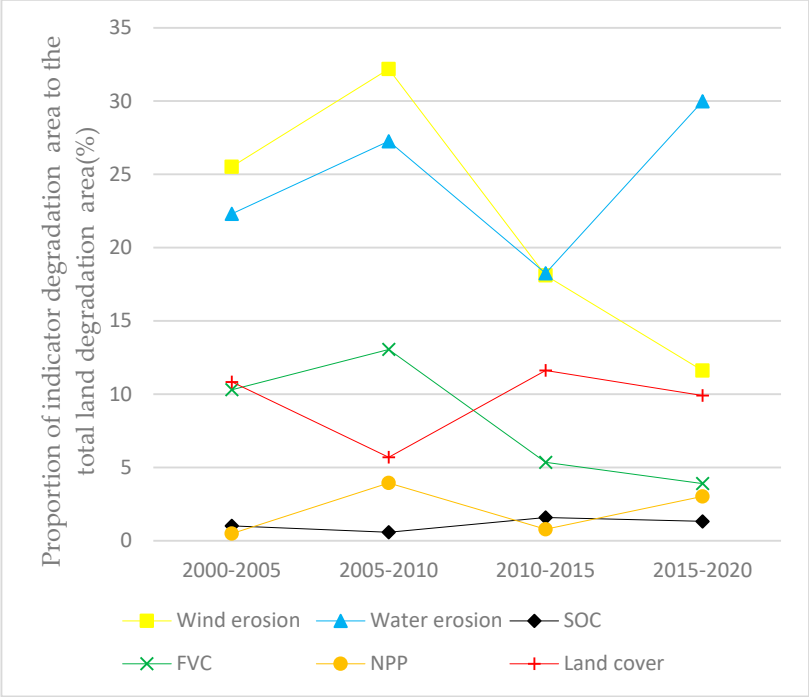


Figure 3. Proportion of each land degradation form area.

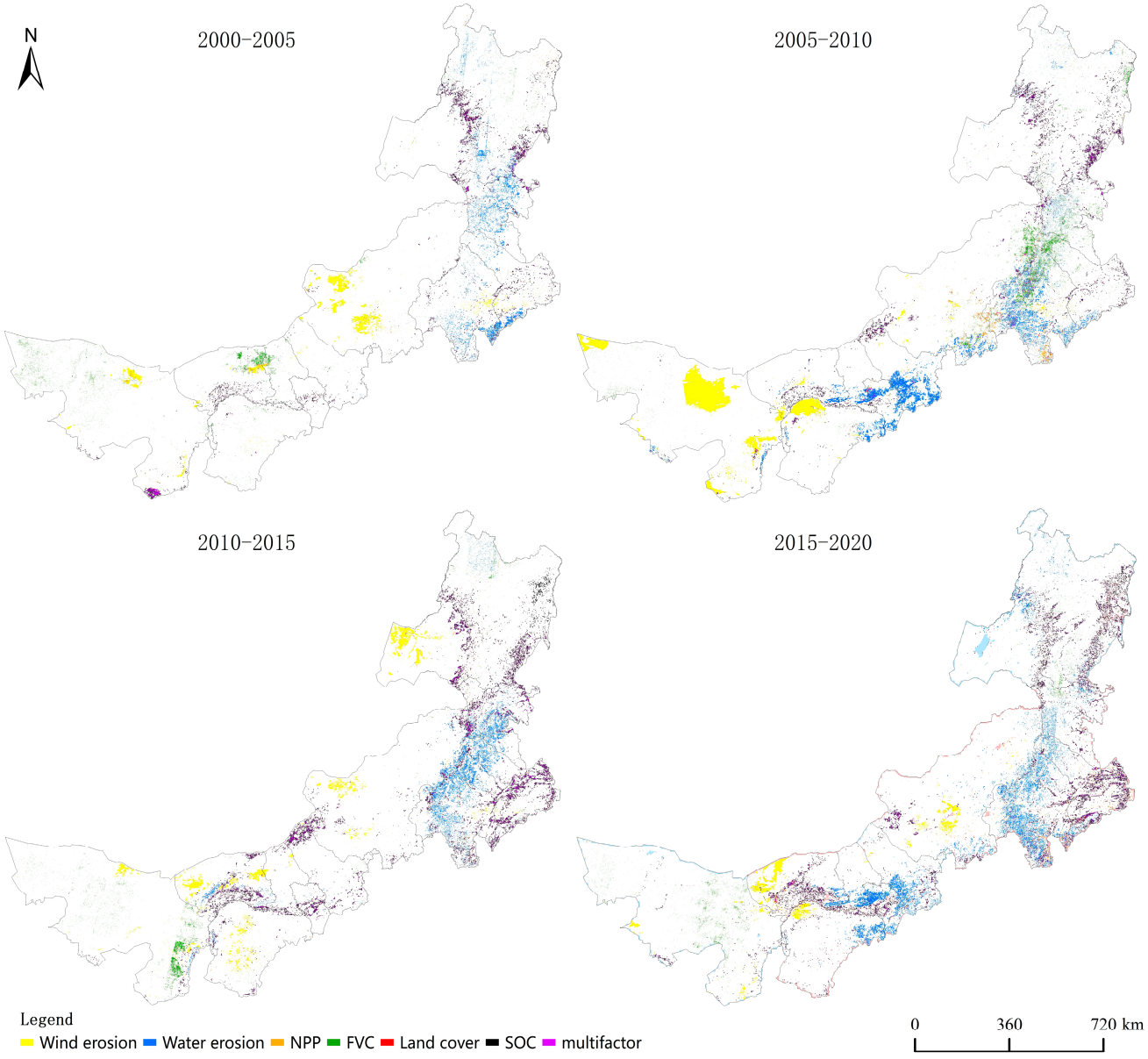


Figure 4. Spatial–temporal distribution of land degradation forms in study area.

In terms of improvement manifestations, as shown in Figures 7 and 8, the main form of land improvement in the study area was the positive changes of NPP and wind erosion. It can be seen that the NPP improvement was mainly distributed in the eastern region in the first period, and the coverage of it was much higher than the other forms. This was mainly due to the general improvement of vegetation growth caused by the continuous increase in precipitation. Thereafter, the unreasonable grazing and grassland reclamation hindered the healthy growth of vegetation in the central and eastern regions, which made the land improvement situation continuously decline. Due to the project of wind prevention and sand fixing, wind erosion in the central and western regions was effectively curbed, making it the most important form of land improvement in the fourth period.

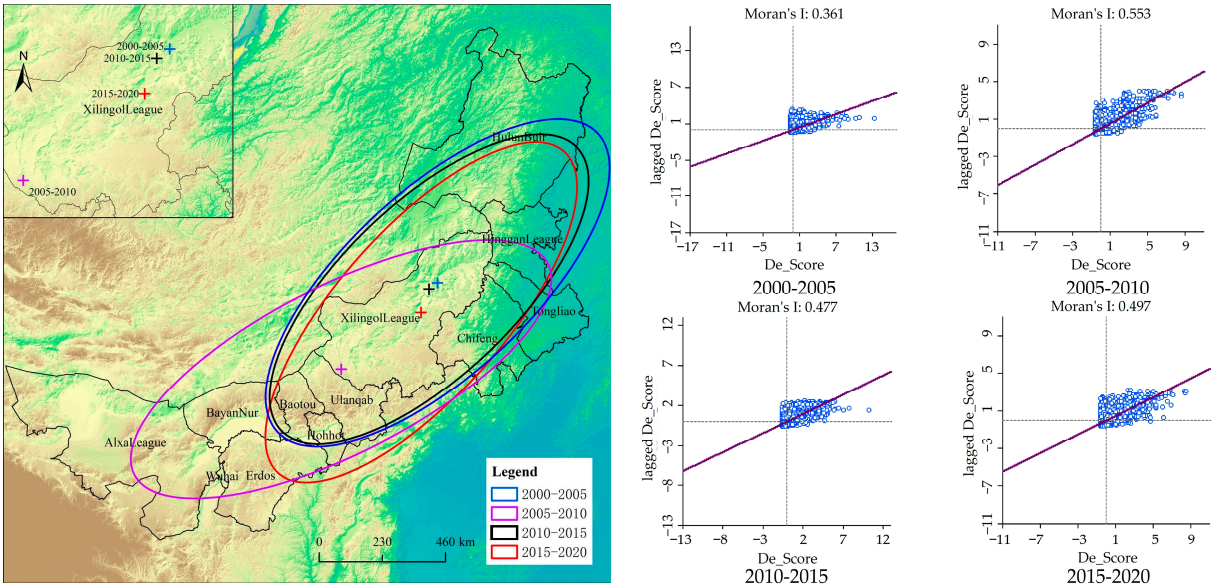


Figure 5. (**a**) Spatial–temporal distribution of land degradation; (**b**) Moran scatterplot of land degradation degree.

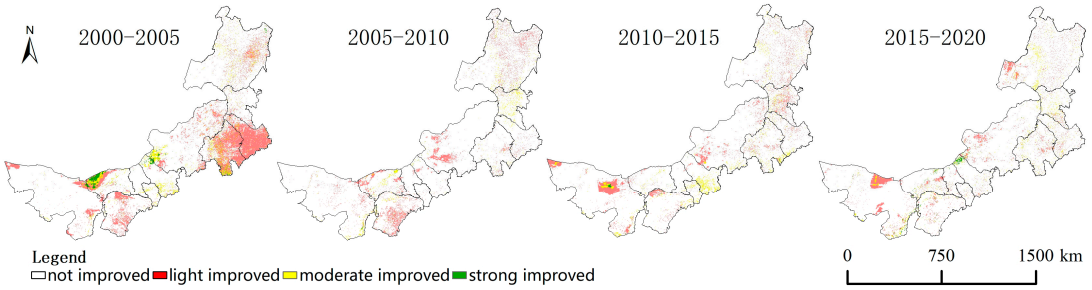


Figure 6. Land improvement in study area.

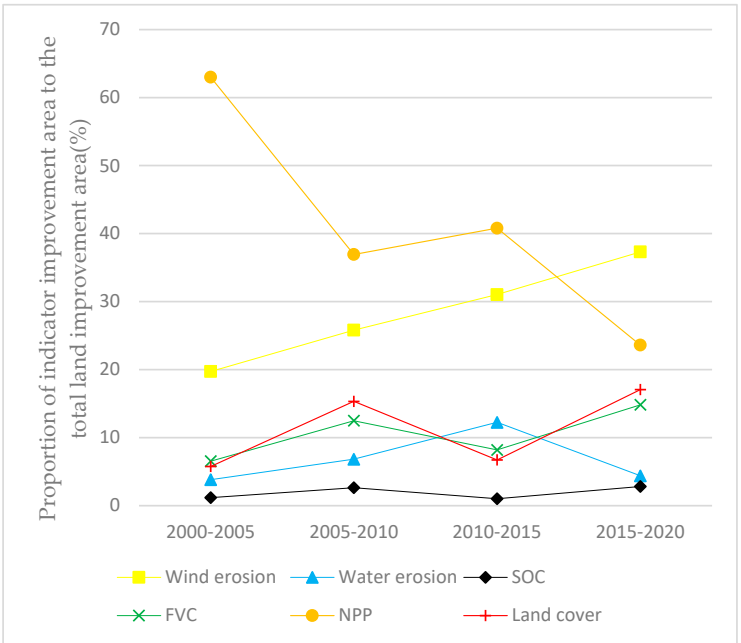


Figure 7. Proportion of each land improvement form area.

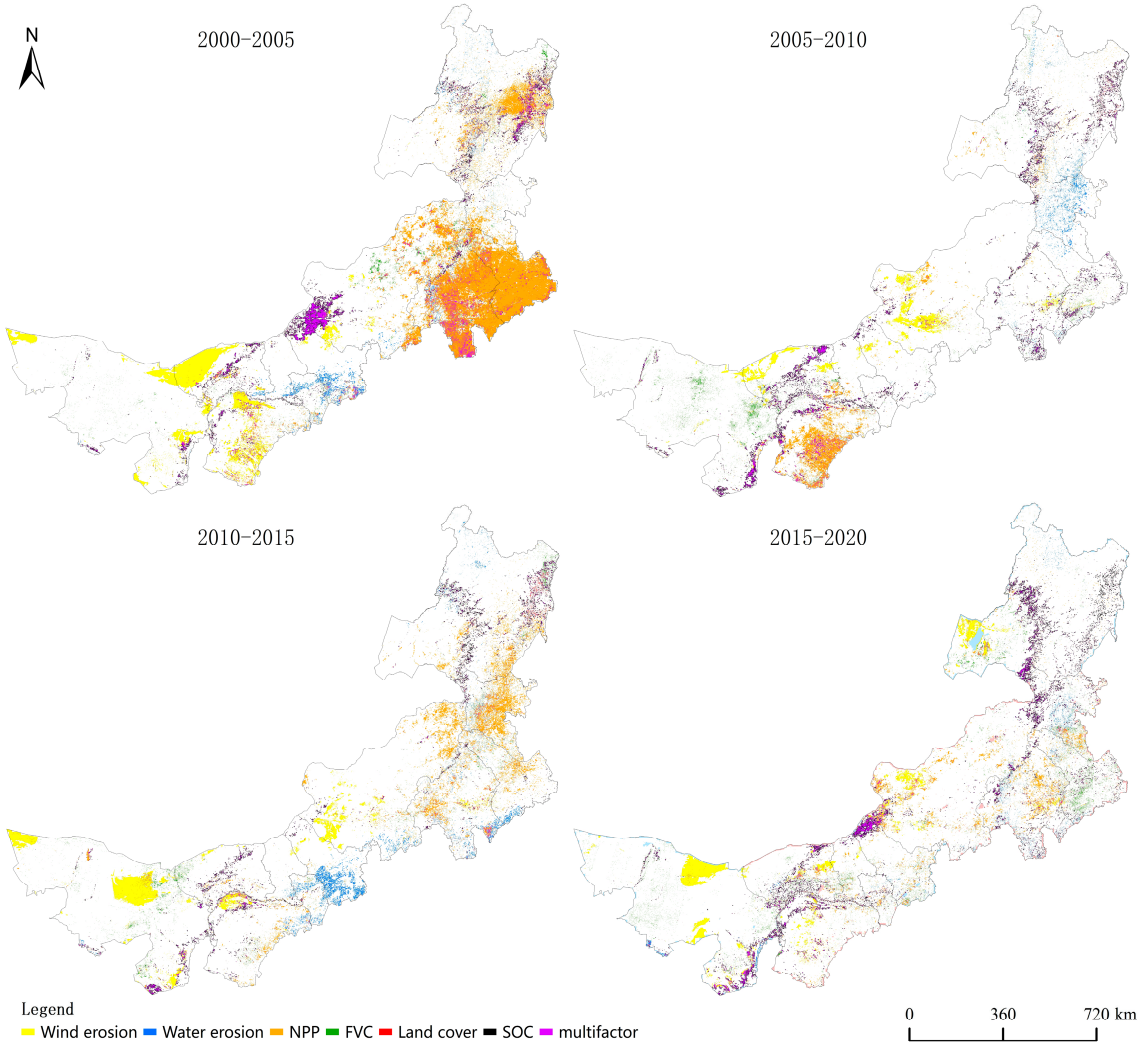


Figure 8. Spatial–temporal distribution of land improvement forms in study area.

In terms of spatial–temporal distribution, as shown in Figure 9a, the land improvement in the study area was distributed in the direction of "northeast–southwest". During the study period, the distribution center moved from east to west, with small changes in the north and south. This shows that compared with the eastern region, the land improvement in the western region was more obvious. From the changes of the long and short semiaxes, the short semiaxis decreased from 372.0 km to 317.1 km, indicating the land improvement was shrinking in the direction of "northwest–southeast" with certain aggregation phenomena. By 2020, the long semi-axis increased from 691.1 km to 952.8 km, which indicates that the land improvement was spreading in the main direction during this period. From a spatial correlation perspective, as shown in Figure 9b, Moran's I of land degradation increased from 0.700 to 0.523, and the Z-score was always higher than 1.96, with the *p*-value always lower than 0.05. This indicates that the land improvement in Inner Mongolia had a significant positive spatial correlation and a certain aggregation effect, and the degree of aggregation gradually weakened. During the study period, most regions were located in the first and third quadrants. This indicates the pattern of land improvement aggregation primarily characterized by the pattern of land improvement aggregation in Inner Mongolia is mainly characterized by high–high degree improvement aggregation and low–low degree improvement aggregation.

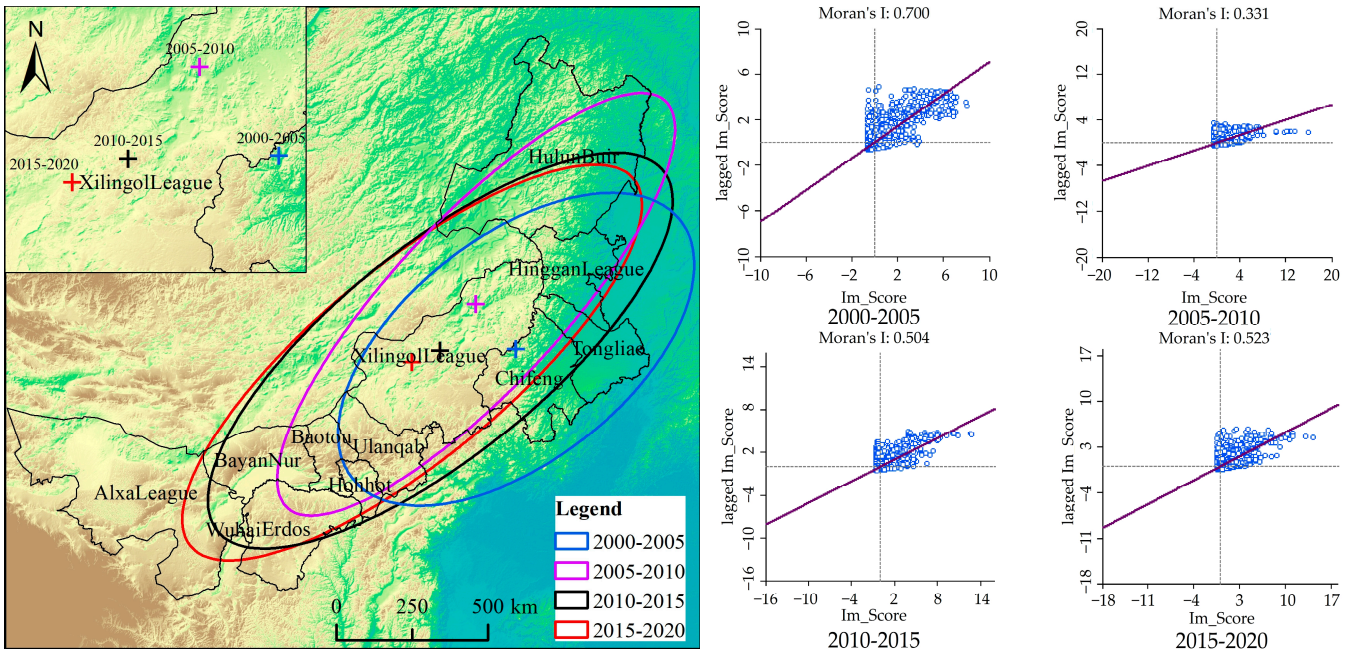


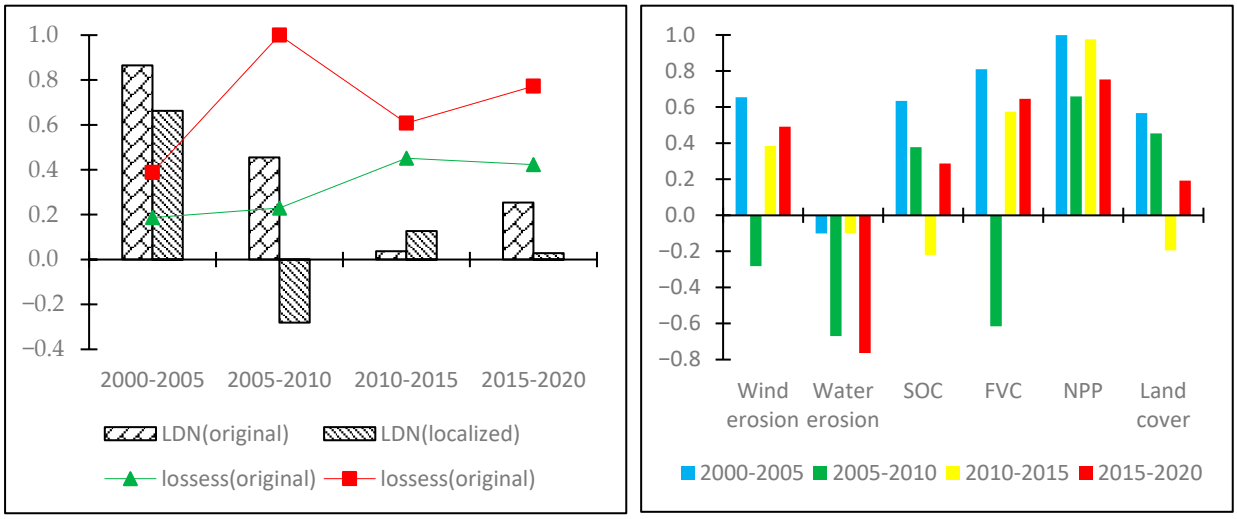
Figure 9. (**a**) Spatial–temporal distribution of land improvement; (**b**) Moran scatterplot of land improvement degree.

3.2. Assessment of SDG15.3 Progress in Study Area over the Last 20 Years

3.2.1. SDG15.3 Progress at Provincial Level

The LDN level of Inner Mongolia was assessed, respectively, through the original indicators in GPG (NPP, SOC, land cover) and the localized indicator system(NPP, SOC, land cover, FVC, wind erosion, and water erosion), the results are shown in Figure 10a. In terms of the original indicators, the LDN level decreased first and then increased during the study period, and was always higher than 0, which means that the requirements of SDG15.3 were met. From the perspective of the localized indicator system, the LDN level was the highest in the first period and decreased to below 0 in the second period, which was lower than the minimum standard of LDN. Although it was always higher than 0 in the third and fourth periods, there was a downward trend. This indicates that land degradation management in the study area can produce obvious effects, but still needs continuous input to stabilize the result of sustainable development and avoid the rebound of land degradation. In addition, there are significant differences in the LDN assessment results obtained using the original indicator system and the localized indicator system, the former always assesses the total loss of land resources to be obviously lower than the latter, which indicates that the original indicators cannot reflect the land degradation situation in Inner Mongolia comprehensively.

In terms of indicator level, as shown in Figure 10b, the NPP was the only indicator that reached LDN in all four periods, the LDN level was always high. The LDN levels of wind erosion, SOC, FVC, and land cover all showed a decreasing trend and then increased, and all achieved the LDN in 2020, indicating that the ecological project such as the wind-prevention and sand-fixing Grain for Green Project in the study area achieved remarkable results. However, the LDN level of water erosion fluctuated and was always below the minimum standard of LDN. This indicates that although Inner Mongolia reached LDN in 2020, there was still a problem of incomplete development and water erosion.



(**a**) (**b**)

Figure 10. (**a**) LDN and land sources losses in study area; (**b**) LDN level of each indicator in study area.

3.2.2. SDG15.3 Progress at Municipal Level

At the municipal level, Figure 11 shows that the number of regions achieving LDN trended downwards. By 2020, only BayanNur, Hohhot, and Tongliao had not achieved LDN, indicating a great spatial unevenness in the sustainable development of land resources in Inner Mongolia. During the study period, the LDN level of Xilingol League, Wuhai, and Erdos was the most stable and consistently met the SDG15.3 standards. The LDN level of Alxa League, Hinggan League, and Chifeng fluctuated noticeably in the early stage of the research, but in the past decade, they have stabilized and met the requirements of SDG15.3. On the other hand, the LDN level of Ulanqab and Baotou has improved noticeably and reached SDG15.3 in 2020.

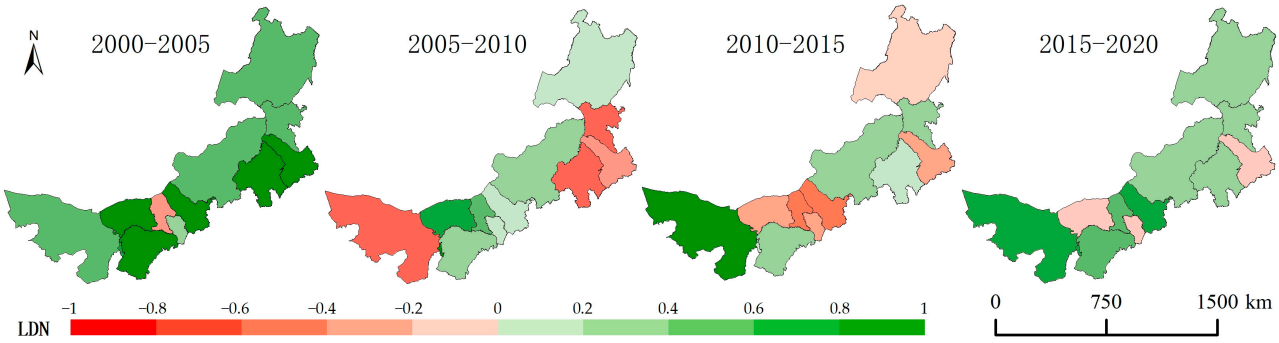


Figure 11. The level of LDN for each indicator at the municipal level in study area.

3.2.3. SDG15.3 Progress at County Level

At the county level, Figure 12 shows that the number of counties achieving LDN showed a decreasing trend. Similar to the municipal scale, the LDN levels at the county scale were also greatly uneven in space, or even worse. The decrease in LDN level was most obvious in the second period, with the mean value decreasing from 0.52 to −0.26. Only 39 out of 103 banners/counties achieved LDN, 42 fewer than in the first period. In the third period, the average value of LDN was 0.05 and decreased to −0.02 in the fourth period. By 2020, a total of 32 banners/counties had achieved LDN, mainly in the western region and the northern central region, while most areas in the eastern region with abundant precipitation, dense vegetation, high soil retention capacity, and carbon sequestration capacity had not achieved LDN, because they were not the focus of land

degradation management. However, their LDN level still had some advantages compared with the southeastern fringe areas where water erosion was becoming increasingly severe.

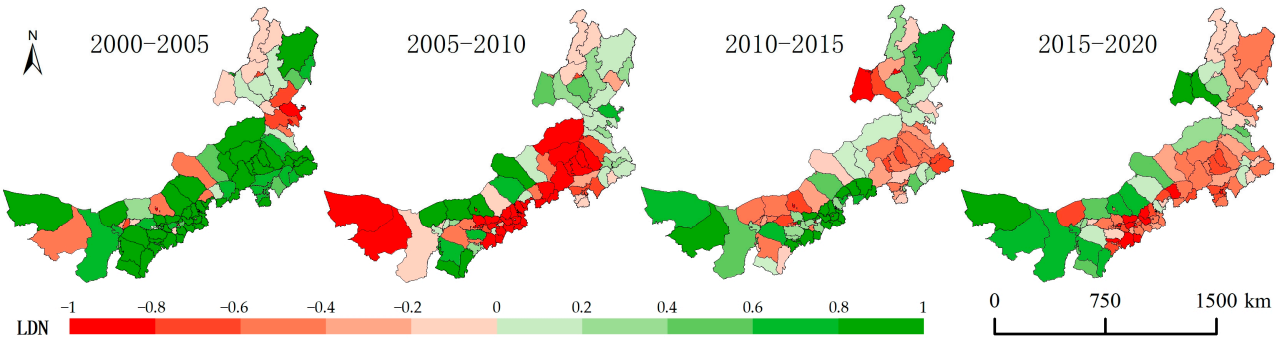


Figure 12. The level of LDN in study area at the county level.

4. Discussion

The contribution of this study is to provide an overall research framework for assessing SDG15.3 at the local level. In consideration of the connotation of SDG15.3, in order to better reflect reality and achieve SDG15.3, LDN was taken as an evaluation index for SDG15.3 instead of SDG15.3.1. Furthermore, considering the different contexts between regions, this paper carried out a localization reform on the original land degradation indicator system in GPG by adding indicators that can reflect the main forms of land degradation (such as soil erosion and desertification) in Inner Mongolia, and improved the unreasonable parts of the original land degradation assessment criteria when applied to Inner Mongolia based on local policies, in order to establish a local-level SDG15.3-oriented localized land degradation and improvement assessment system. The proposed localized assessment system is more comprehensive and representative than the original indicators, which can be reflected in the following aspects: (1) it proposes the SDG15.3 assessment method based on the degree of degradation and improvement weighted area, which improves the deficiency of the original scheme that only focuses on area, making it more scientific, reasonable, and practical; (2) it can quantitatively assess LDN at the local level, reveal the progress of sustainable development of land resources, highlight the work and effectiveness of local governments at all levels to achieve SDG15.3, and provide a reference for similar studies on sustainable development of land resources at a local level.

Inner Mongolia Autonomous Region is located in the arid and semi-arid area in the northwest of China, with low vegetation coverage, uneven terrain, soil structure evacuation, less and uneven precipitation, and high and frequent winds. These natural conditions, combined with year-round unreasonable farming and animal husbandry activities, make the land degradation here extremely serious. In this study, the LDN levels in FVC, NPP, and land cover declined from 2000 to 2010, which may be caused by climate change and overgrazing. According to the research conducted by Qin et al., 2007 and 2010 were the most severe drought years in Inner Mongolia since 2000, which largely led to the decline of the aforementioned indicators, especially FVC [47]. However, from 2010 to 2020, those indicators show an upward trend due to the proactive efforts of the local government to implement various ecological protection and restoration projects, such as the Implementation Plan for the New Round of Grain for Green Project and the construction of the "Three North" shelter forest system. By 2020, 4.11 million mu of barren, desertified farmland and steep slope farmland were successfully converted to forests and grasslands. Furthermore, Inner Mongolia's enforcement of the system of basic grassland protection, grazing and livestock balance, and rotation of grazing effectively enhanced the grasslands in Hulunbuir, Horqin, Xilin Gol, and the northern foot of Yinshan. These measures not only resulted in a forest coverage rate of 23%, but also greatly improved the grassland vegetation coverage to 45% across the entire region, leading to a positive impact on land carbon storage. This also explains the significant increase in the LDN at the SOC level from

2010 to 2020. Thus, the ecological protection and restoration projects implemented by the Inner Mongolia government have effectively improved the local land resources, and such initiatives should be sustained in future endeavors.

Affected by special natural conditions, soil erosion in Inner Mongolia has a wide distribution and high intensity, endangering ecological security, food security, life and property security, and seriously restricting the sustainable development of the regional economy and society. For this reason, the Water Resources Department of Inner Mongolia Autonomous Region issued the Water and Soil Conservation Plan of Inner Mongolia Autonomous Region, proposing that "by 2020, the area where soil erosion has been controlled will be increased by 30,800 km^2", and undertaking a series of actions in response to this. Despite this, improvement in soil erosion has been uneven, with changes in wind erosion and water erosion showing contrasting trends. Among them, wind erosion has significantly improved and met the LDN standard, which can be attributed to measures such as fencing protection and natural restoration that have effectively increased the coverage of forests and grasslands, thus enhancing the conservation of water and soil. However, water erosion in Inner Mongolia has severely worsened and has never met the LDN standard. This could be attributed to changes in precipitation, which acts as an external driving force for water erosion. Research conducted by Gao et al. shows that the annual precipitation in Inner Mongolia has generally increased since 1970 [48], lending support to the above theory. In summary, the changes in soil erosion could be attributed to both natural and human factors. Actions such as fencing protection and natural restoration effectively improved soil erosion and the area of improvement reached 37,800 km^2, exceeding the expected goal (30,800 km^2). However, the increase in precipitation still exacerbates the worsening of water erosion. Thus, Inner Mongolia should implement more targeted measures to control water erosion, such as constructing sediment dams and implementing slope improvement in cultivated slopes.

In summary, the Three-North Shelterbelt Project, Grain for Green Project, and the ecological construction of soil and water conservation have achieved great success in the Inner Mongolia Autonomous Region: the land degradation has been well controlled, the vegetation cover and forest cover have increased significantly, and the soil erosion has improved generally. Thus, those measures should be sustained in future endeavors. Whereas, targeted measures should be taken in areas along the southeast edge where water erosion is serious. Such measures include small retention and drainage projects that integrate check dams, reservoirs, and drainage ditches to reduce erosion and scouring in channels and slopes, as well as reforestation projects on barren slopes and abandoned cropland.

5. Conclusions

A localized indicator system for SDG15.3 has been developed based on the natural conditions of Inner Mongolia. Through this system, we have quantitatively evaluated the degree of land degradation and improvement, analyzed the spatial–temporal distribution of land degradation, and quantitatively assessed the progress of SDG15.3 in Inner Mongolia.

The results show that, overall, land degradation in Inner Mongolia has been effectively controlled, with a reduction in the area, scope, and intensity of degradation, while the scope and intensity of land improvement have generally increased. In terms of spatial distribution, the situation of land degradation in the west is more serious than that in the east, but the improvement of land resources is also more obvious, while in the southern region where the situation of land degradation is serious, the improvement of land resources is relatively weaker. The LDN assessment results show that Inner Mongolia had achieved the "Land Degradation Neutrality" required by SDG15.3 on the whole, but the development did not reach the goal at the indicator level, such as water erosion, the main form of land degradation. This indicates that water erosion became a major obstacle to the continuous promotion of sustainable development in Inner Mongolia. The LDN level at the municipal and county level was extremely uneven, most of the municipal regions had not achieved LDN, and the LDN level at the county level showed an obvious distribution pattern of

low in the southeast and high in the northwest. Inner Mongolia should strengthen water erosion control, and improve the soil and water conservation capacity of the eastern and southern marginal areas, to promote LDN in an all-round and all-dimensional way.

There are also some shortcomings in this study. Firstly, although the localized indicators can reflect the main forms of land degradation in the study area, there is still no indicator of land pollution, salinization, or other forms of land degradation due to the difficulty of data acquisition. The comprehensive combing of degradation representations needs to be further strengthened. Additionally, this paper only analyzes the spatial–temporal distribution characteristics of land degradation, and the quantitative analysis of the influence mechanism of land degradation is still lacking, which is the focus of the next research.

Author Contributions: Conceptualization, Z.L. and Y.W. (Yanhui Wang); Formal analysis, Z.L.; Funding acquisition, Y.W. (Yanhui Wang); Investigation, Z.L., J.D. and X.L.; Methodology, Z.L. and Y.W. (Yanhui Wang); Software, Z.L.; Supervision, Y.W. (Yanhui Wang); Validation, Z.L.; Writing—original draft, Z.L.; Writing—review and editing, Y.W. (Yanhui Wang); J.D., X.L., Y.W. (Yuan Wan) and H.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Natural Science Foundation of China (grant numbers 42171224, 41771157), National Key R&D Program of China (grant numbers 2018YFB0505400), the Great Wall Scholars Program (grant numbers CIT&TCD20190328), Key Research Projects of National Statistical Science of China (grant numbers 2021LZ23), Young Yanjing Scholar Project of Capital Normal University, and Academy for Multidisciplinary Studies, Capital Normal University.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data will be available at a reasonable request from the corresponding author.

Conflicts of Interest: The authors have declared that no competing interest exist.

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