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Quantitative Analysis of Land Degradation in Mongolia from the Perspective of Geographical Zone

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Abstract: Natural and anthropogenic disturbances accelerate land degradation (LD) in arid, semi-arid, and dry sub-humid areas, leading to reduced land quality and productivity, loss of biodiversity, degradation of ecosystem services, and a decline in the quality of life of local people. To address this issue, the United Nations Convention to Combat Desertification (UNCCD) has set a target for LD neutrality (LDN). However, quantifying and comparing the status of LD at global or regional scales remains challenging due to the lack of coherent quantitative methods and tools. In this study, we focused on Mongolia, a region with significant LD problems, to examine patterns of LD and changes from 2015 to 2020, accounting for regional differences. Trends.Earth was used, as recommended by the UNCCD. The main findings are as follows: (1) Overall, the degraded land area in Mongolia accounted for 12.11% of the total land area, predominantly located in the southwest desert and desert steppe, gradually spreading to the northeast steppe. (2) The areas showing improvement in the land productivity index and degradation were 17.62% and 11.79%, respectively, with the most severely degraded areas concentrated in the southern desert and desert steppe regions. (3) The areas of improvement and degradation in the land cover index were 1.80% and 0.16%, respectively, with degraded areas scattered across regions of steppe, high mountains, and mountain taiga. (4) The areas of improvement and degradation in the land organic carbon index were 1.54% and 0.22%, respectively, with degradation primarily observed in adjacent areas of mountain taiga, steppe, and desert steppe. (5) The improved area (2.999×10^5 km^2) of LDN are more than the degraded area (1.895×10^5 km^2), indicating a positive trend toward LDN in Mongolia.

Key words: geographical zone; land degradation; land degradation neutrality; Mongolia; Trends.Earth

1 Introduction

Land degradation (LD) refers to the "continuous reduction or loss of the productivity of the land due to a combination of natural and anthropogenic causes" (UNCCD, 1994). It is a pressing global issue necessitating a comprehensive approach to ensure sustainable land use and safeguard ecosystems worldwide. This concern has garnered international attention, notably from the United Nations Convention to Combat Desertification (UNCCD). In 2016, UNCCD proposed the LD neutrality (LDN) target, aiming to maintain or enhance the quantity and quality of land resources to support ecosystem functions, services, and food security within specific tem-

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poral and spatial scales and ecosystems (Grainger, 2015). LDN constitutes a key indicator of United Nations Sustainable Development Goal (SDG) 15.3.1, which aims to halt and reverse LD.

However, there has been a dearth of quantitative indicators and tools for assessing LD, particularly on a global or large regional scale. The UNCCD Science-Policy Interface (SPI) has identified core indicators for monitoring global LD: productivity, land cover, and soil organic carbon (SOC). These indicators better define the rules for LDN implementation and guide the establishment of LDN monitoring systems, offering a crucial reference for global standardisation in identifying LD (Giuliani et al., 2020a). If any sub-indicator shows negative trends (or remains stable when degraded in the baseline or previous monitoring year) for a specific land unit, it is considered degraded, subject to validation by national authorities. This precautionary approach is necessary because stability or improvements in one indicator cannot offset degradation in others.

To prioritise the conservation of biodiversity and ecosystem services vital for life on Earth, efforts to avoid, reduce, and reverse LD must be intensified. Halting and reversing the current trend of LD are paramount. Achieving this goal requires enhancing national capacity for quantitative assessment and mapping of degraded land, in line with the SDGs. Specifically, SDG indicator 15.3.1 underscores the importance of such assessments and mapping to align with sustainable development objectives. To this end, UNCCD has recommended the global application of the Trends.Earth tool (Cherif et al., 2023).

Combined with these concepts and quantitative assessment tools, numerous scholars have conducted relevant research. Wang utilised national desertification and desertification monitoring data to compare and analyse the LDN index based on the UNCCD framework. They proposed a desertification LD index in China, based on changes in the degree of land desertification (Wang et al., 2023). Cherif et al. analysed LD in Greece and Tunisia using the LDN framework, demonstrating that the largest proportion of degraded land in Greece was grassland, while in Tunisia, it was cropland for cereals (Cherif et al., 2023). Zhao conducted a comprehensive evaluation of land status in the entire region and the ecological planning area of Inner Mongolia. They demonstrated that the proportion of land restoration in each ecological project and the entire region continues to increase (Zhao et al., 2023). Reith conducted a study on the extent of LD in semi-arid zones of Tanzania, combining local datasets with high-resolution imagery. They implemented sustainable land management practices based on fine-grained resolution results (Reith et al., 2021). Solomun reported trends in the sub-indicators of Republika Srpska, an entity of Bosnia and Herzegovina. They identified and validated that the most common direct drivers of LD in the region are land abandonment, floods, drought, erosion, and urbanisation, with potential drivers being population decline and migration to central cities (Solomun et al., 2018). Many studies have also focused on LD in areas surrounding the Mongolian plateau (Hu and Xu, 2014; Zhang et al., 2018; Zheng et al., 2023). However, most studies consider Mongolia as a whole and do not analyse it in the context of the country's geographical differentiation.

Trends.Earth Version 2.1.14 is a scalable land monitoring tool that facilitates global monitoring and assessment of land cover, LD, and restoration potential. At a small scale, Trends.Earth can analyse individual plots or regions, while also providing comprehensive land monitoring and assessment at the national or regional level. In this study, we utilised the three indicators of LDN to conduct a regional assessment of LD in Mongolia. We divided Mongolia into six physical regions (high mountain, mountain taiga, forest steppe, steppe, desert steppe, and desert) to evaluate existing problems and the effectiveness of ecological restoration from the perspective of geographical zoning. We then developed a new multi-scale application of Trends.Earth, providing a focused scientific basis for future ecological restoration management in Mongolia.

2 Materials and methods

2.1 Study area

Mongolia (87°44′–119°56′E, 41°35′–52°09′N) is situated in the arid and semi-arid regions of Eurasia, with an average altitude of approximately 1580 m and an annual average precipitation of approximately 269 mm (Zheng et al., 2023). The land cover in the study area is zonally distributed, ranging from desert, desert steppe, steppe, forest steppe, mountain taiga to high mountain, from south to north. The regional climate is characterised by a continental temperate steppe climate, featuring severely cold winters and hot summers (Angerer et al., 2008), with significant seasonal variations. Mongolia is predominantly covered by natural grasslands and is considered a typical pastoral area (Jiao et al., 2021), with abundant grassland resources and animal husbandry as its primary economic activity (Goenster-Jordan et al., 2018).

2.2 Methods

Trends.Earth Version 2.1.14 is a scalable land monitoring tool that offers the following features (Gonzalez-Roglich et al., 2019): 1) Provision of global data covering different time horizons for monitoring and assessing LD; 2) Support for cloud computing in the region of interest to obtain three indicators of LDN; 3) Combination of the three indicators into SDG 15.3.1 following the principle of the one-out all-out rule (1OAO).

The baseline period was set from 2001 to 2015, and the monitoring period spanned from 2015 to 2020. The baseline period of 2001–2015 encompasses 15 years, excluding 2015, covering the years from 2001 to 2014, inclusive. The calculation process of SDG 15.3.1 is depicted in Fig. 1, and the dataset is provided in Table 1.

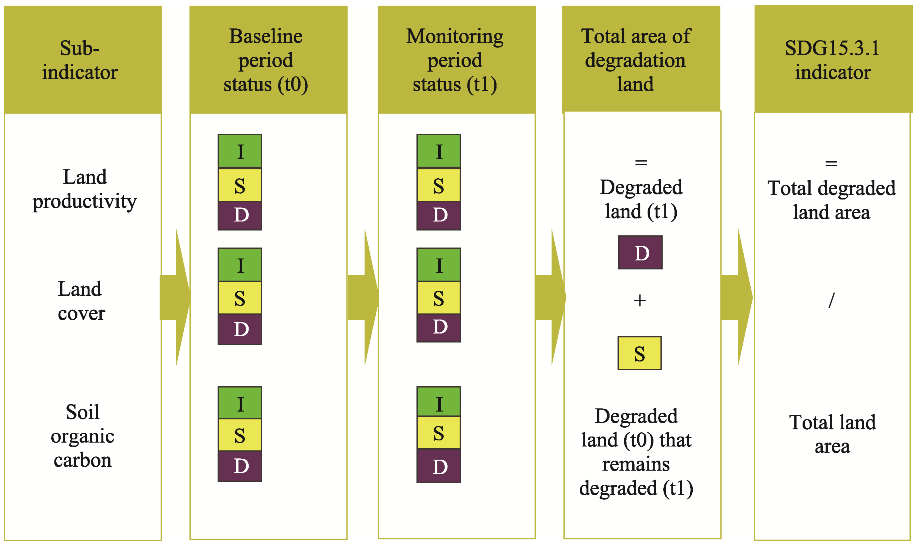

Fig. 1 Calculations steps for SDG 15.3.1 indicator

Table 1 Data sets utilised in this study

SDG15.3.1 Sub-indictors	Data	Resolution	Data resource
Land productivity	MOD13Q1-coll6	250 m	LP DAAC-(usgs.gov)
Land cover	ESA-CCI	300 m	www.esa-landcover-cci.org
Soil organic carbon	SoilGrids	250 m	www.soilgrids.org

2.2.1 Land productivity

Productivity denotes a soil's capacity to yield crop production and sustain existing biomass within the ecosystem (Bernard et al., 2022). Net primary production (NPP) signifies plants' ability to utilise substances obtained through photosynthetic carbon fixation (Zhao and Running, 2010). Here, the normalised difference vegetation index served as a proxy indicator of NPP to depict changes and vegetation growth (Fensholt and Proud, 2012; Wen et al., 2017). For SDG15.3.1 reporting, a three-class indicator (Improved, Stable, and Degraded) is mandated, but Trends.Earth also furnishes a five-class variant (Improved, Moderate decline, Stable, Stressed, and Degraded) utilising state information to discern degradation types.

2.2.2 Land cover

Land cover indicators delineate transitions between land cover types and were computed following these steps (Giuliani et al., 2020b): 1) Reclassify both land cover maps into the seven required classes for UNCCD reporting (forest, grassland, cropland, wetland, artificial area, bare land, and water); 2) Conduct a land cover transition analysis to identify pixels maintaining the same class and those altering. The association between land cover conversion type and land state is depicted in Table 2, denoted by "+" for improved, "–" for degraded, and "0" for stable; 3) Generate level three indicators of land cover types (degraded, stable, and improved).

2.2.3 Soil organic carbon

Due to the absence of a SOC database in Mongolia, a combined land cover and SOC approach was employed to pinpoint potential degraded areas (Hengl et al., 2017). The relative difference between baseline and reporting periods was calculated, with areas showing a decline exceeding 10% deemed potentially degraded, and those rising by 10% or more considered potential improvements.

Table 2 Relationship between land cover conversion types and land condition

	Land cover type in 2020							
	Land cover type	Forest	Grassland	Cropland	Wetland	Artificial area	Bare land	Water
Land cover type in 2015	Forest	0	–	–	–	–	–	0
	Grassland	+	0	+	–	–	–	0
	Cropland	+	–	0	–	–	–	0
	Wetland	–	–	–	0	–	–	0
	Artificial area	+	+	+	+	0	+	0
	Bare land	+	+	+	+	+	0	0
	Water	0	0	0	0	0	0	0

3 Results

3.1 Change in productivity

The MOD13Q1-coll6 dataset, obtained through Trends. Earth, yielded the land productivity map depicted in Fig. 2. From 2015 to 2020, productivity indicators remained generally stable. The area of improved and degraded land measured 2.76×10^5 km^2 and 1.84×10^5 km^2, respectively, constituting 17.62% and 11.79% of Mongolia's total land area.

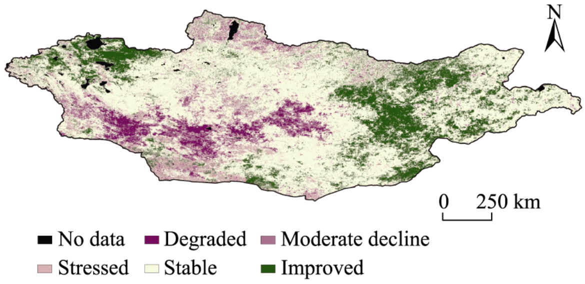

Fig. 2 Assessment of land productivity indicators (2015–2020)

Improved productivity areas were widely distributed across each region, with concentrations noted in the desert steppe and northeastern steppe. Degraded productivity areas were concentrated in the north and south of Mongolia. Common characteristics of degraded areas included the complexity and diversity of internal geographical zones, with more severe land productivity degradation observed in the southern desert and desert steppe regions. The geographical subdivisions of the northern forest steppe and mountain taiga exhibited an early trend of declining land productivity.

From a regional perspective, areas of degraded productivity in northern Mongolia were dispersed across Khuvsgul, Bulgan, Gohangai, Selenga, southwestern and northeastern Central Province, and northwestern Kent. In Khuvsgul, degraded productivity trends were observed in the northern high mountains, mountain taiga, and steppe, while productivity indices in the southern region remained stable. Bulgan's degraded productivity areas were situated in the mountain taiga region, while the forest steppe generally maintained stability, albeit with early signs of declining productivity in several areas. Houhangai exhibited widespread early signs of degraded productivity in the forest steppe and high mountain regions. Selenga showcased an early trend of degraded productivity in the forest steppe. In the southwestern and northeastern portions of Central Province and northwestern Kent, which fall under the mountain taiga regions, productivity indices showed early signs of decline.

In southern Mongolia, areas with productivity indicators signalling degradation were primarily found in Khobdo, Gobi Altai, Bayanhongor, Qianhangai, and the western portion of the Middle Gobi. The productivity indicator in the high mountain and steppe regions of the central Kobdo Province experienced a decline, gradually spreading to the north and south. The geographical subdivisions of Gobi, Altai, and Bayankhongol are intricate, with areas experiencing significant declines mainly situated in alpine and steppe zones. Qianhangai regions experienced downward pressure on land productivity, with widespread declines observed in grassland and desert steppe areas, alongside signs of decline in the northern forest steppe and southern desert regions. The Middle Gobi region's areas with severe land productivity decline were also located in the desert steppe, with adjacent steppe and desert steppe zones showing early signs of declining productivity.

3.2 Change of land cover

A land cover indicator was derived from ESA-CCI7 land cover data (Fig. 3). The degraded and improved land cover areas measured 2.81×10^4 km^2 and 2.53×10^3 km^2, respectively, accounting for 1.8% and 0.16% of Mongolia's total area, respectively.

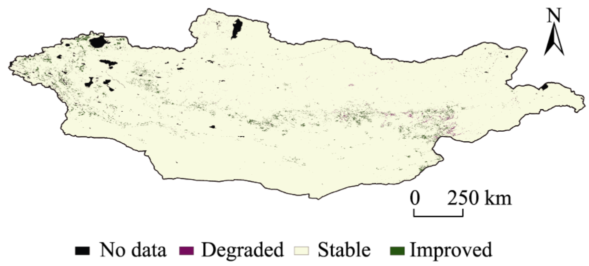

Fig. 3 Assessment of land cover indicators (2015–2020)

The land cover indicator for Mongolia depicted stabilisation in most areas, with scattered degradation zones. Degraded areas were primarily situated at the junction of the central steppe and desert steppe geographical regions, as well as in the northern forest steppe geographical region. The degraded zones were dispersed, encompassing the Ubusu desert steppe, the eastern high mountains of Bayanhongor and Ulaanbaatar, and the mountain taiga regions of northeastern Central Province and northwestern Kent.

Regionally, improvements in land cover were evident in the steppe and desert steppe regions, spanning from Zabhan, Bayanhongor, Qianhangai, Central Province, Middle Gobi, East Gobi, to Sukhbaatar Province, from west to east. In Zhabkhan, improvements were observed in the western desert steppe and the northern and southern steppe, with the desert steppe exhibiting greater improvement than the steppe. Bayanhongol showcased improved land cover within the steppe, while Khentii Province saw concentrated improvements in the central region, with lesser improvement in the northern region compared to the central steppe. Central Province demonstrated improvements in the west and southeast, within the steppe region. The western improvement area is close to the Thule River Basin, while the southeast improvement area is close to the Krulun River. In Central Gobi, improved land cover were located in the northern steppe and the junction zone between the steppe and desert steppe. In East Gobi, areas with improved land cover were zonally distributed and mainly located in the desert steppe, with the desert land cover indicator remaining almost stable. Sukhbaatar recorded improvements in the southwestern region, adjacent to the desert steppe improvement area in the northeast of East Gobi Province, with scattered improvement areas in the southwest steppe. Improvement degree increased gradually from west to east in this region. In Khuvsgul, the forest steppe land cover index remained stable, with scattered improvements. In Houhangai Province, improvements were scattered throughout the forest steppe. In Bulgan Province, land cover improvement was observed in the northern forest steppe, while the land cover in the south remained stable. Selenga exhibited distributed improvements in forest and grassland areas. In Central Province, improvement areas were located in the northern forest steppe, although some areas of the mountain taiga adjacent to the forest steppe exhibited decline. In Kent, land cover declines were observed in the mountainous taiga region, while improvements were recorded in the forest steppe, with stable land cover in the steppe. Areas exhibiting degraded land cover were scattered and located in the Ubusu desert steppe, the eastern high mountains of Bayanhongor, the mountain taiga of Ulaanbaatar, northeastern Central Province, and northwestern Kent.

3.3 Change of SOC

Based on the Trends.Earth land cover and SoilGrids dataset combination method, the SOC indicator was derived (Fig. 4). The areas exhibiting improved and degraded SOC values were 2.39×10^4 km^2 and 3.44×10^3 km^2, respectively, constituting 1.54% and 0.22% of Mongolia's total area.

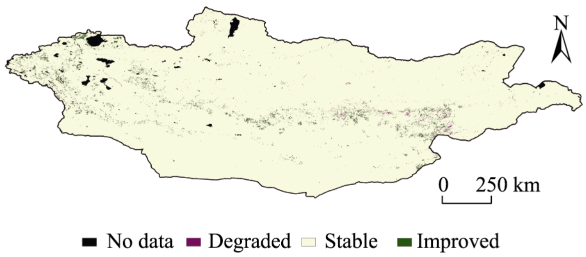

Fig. 4 Assessment of SOC indicators (2015–2020)

Regions with improved SOC were primarily located in the central steppe, southeastern desert steppe, and western high mountains. Progressing from west to east, improved areas included Bayan Uregai, Khobdo, Gobi Altai, Zabhan, Bayanhongor, Qianhangai, and Middle Gobi. Areas with degraded SOC were dispersed across the northern mountain taiga of Central Province, Ulaanbaatar, the northern Central-Gobi steppe, central Gobi Sumber steppe, southern Kent steppe, northern East-Gobi steppe, and adjacent desert steppe.

3.4 LD status in Mongolia

The total areas of improvement and degradation were 2.999×10^5 km^2 and 1.895×10^5 km^2, respectively, representing 19.1% and 12.11% of Mongolia's land area.

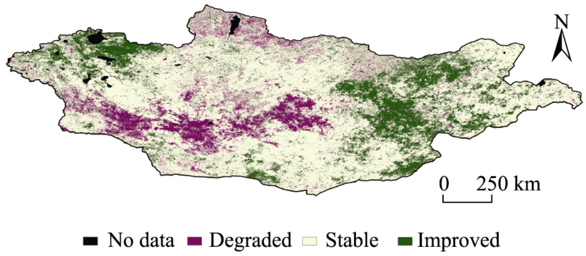

Fig. 5 Evaluation of LDN composite index (2015–2020)

From 2015 to 2020, areas showing improvement were dispersed in the northwest, east, and southwest regions of Mongolia. The northwest and eastern parts exhibited blocky distributions, while improvement in the southwest was scattered. In the northwest, improvement occurred in desert steppe, high mountain, steppe, and forest steppe regions, while in the east, it was observed in desert steppe, steppe, and forest steppe areas. In the southwest, improvement was noted in desert regions, albeit with a weak degree of enhancement. Progressing from west to east, the degraded area traversed the central part of Kobdo, the central and northern Gobi Altai, Bayanhongor, former Hangai, and the western section of the Middle Gobi, forming a distinct degradation belt.

Regionally, the LDN degraded area spanned from the central part of Kobdo to the western part of the Middle Gobi, encompassing the central and northern Gobi Altai, Bayanhongor, Khentii Province, and forming a conspicuous degradation belt from west to east. Scattered degraded areas were observed in the northern part of the study area, including northern Khuvsgul, Bulgan, Selenga, northeastern and southwestern central areas, and southeastern Houhangai and Zabhan.

In Kobdo, the central degraded area comprised desert steppe, steppe, high mountain, and steppe regions from north to south, exhibiting a complex geographical distribution. Central Gobi Altai's degraded areas were predominantly in desert, desert steppe, and steppe, transitioning to desert steppe from north to south. Northern Gobi Altai's degradation areas formed a ring, ranging from alpine to steppe and desert steppe from inside to outside, with higher degradation in the central than in the northern part of the province.

Bayanhongol's central region experienced higher degradation compared to the north and south. Degraded areas were observed in desert steppe, steppe, and high mountain regions in the central part, steppe in the north, and desert in the south. Qianhangai's geography progressed from forest steppe, steppe, desert steppe, to desert from north to south, with degraded areas concentrated in the steppe. In Middle Gobi, degraded areas were mainly in the western steppe and desert steppe.

4 Discussion

This study utilised three core indicators of LDN to assess LD and improvement across various geographic regions of Mongolia from 2015 to 2020. Land productivity saw significant improvement, primarily in the desert steppe and northern steppe regions. A notable increase in maximum spring temperature in Mongolia by 36.38% (P<0.01) aligned with the spatial and temporal pattern of land productivity recovery (Zhang et al., 2023). The consistent factor contributing to declining productivity is the physical complexity and diversity of these regions. Zhang's research on the impact of land use/land cover change, human activities, and climate change on grassland NPP in Mongolia indicated that human activities were the dominant factor in degraded areas, while climate played a significant role in improvement areas (Zhang et al., 2020).

Improved land cover areas were predominantly concentrated in a zone at the confluence of the central steppe, desert steppe, and northern forest steppe regions. Grassland serves as the primary land use, with grazing as the primary activity and reclamation as the main disturbance factor in Mongolia (Wulan, 2021). Degraded land cover areas were dispersed within regions of steppe, high mountain, and mountain taiga. The range of ecosystem changes identified based on this indicator was relatively narrow due to minimal changes in land use and types of land cover in these areas.

Areas showing improvement in SOC were primarily situated in regions of central steppe, southeastern desert steppe, and western alpine areas. Conversely, SOC degradation areas were scattered, mainly adjacent to mountain taiga, steppe, and desert steppe regions. Since the SOC index is calculated by integrating land cover and SOC measures, the calculated results of land cover and SOC exhibit similarities. Research indicates that converting farmland to woodland increases carbon sequestration rate and soil organic matter (Li and Shao, 2006), while the carbon sequestration potential of soil increases when farmland is converted to forest land (Guo and Gifford, 2002). Additionally, soil carbon loss from the conversion of forest to grassland is estimated to be about 20%–30% (Glaser et al., 2000), which aligns with the type of land cover conversion observed in Mongolia from 2015 to 2020.

Examination of LDN revealed that degraded areas were primarily situated in the desert and desert steppe regions of southwest Mongolia, gradually extending into the northeast steppe region. This finding aligns with the results of Chen regarding the distribution of desertification in Mongolia from 2003 to 2017 (Chen et al., 2019), as well as with Zheng's study on LDN in the Mongolian Plateau from 2011 to 2020 (Zheng et al., 2023). While Zheng et al. focused on the period from 2011 to 2020 with a baseline period from 2001 to 2010, our study examined the period from 2015 to 2020 with a baseline from 2001 to 2015. Our findings indicate that from 2015 to 2020, LDN degradation areas in Mongolia were concentrated in central Khovdo, central and northern Gobi Altai, Bayanhongor, the former Hangai, and western Middle Gobi. Additionally, scattered degraded areas were observed in northern Khuvsgul, Bulgan, Selenga, the northeast and southwest of the central government area, and southeastern Houhangai and Zabhan. In conclusion, our study aligns with Zheng et al.'s conclusion that the Mongolian Plateau region reached the LDN target in 2020 relative to the ecosystem state in 2001–2010. Furthermore, we find that Mongolia achieved its LDN target in 2020 compared to 2001–2015. Unlike Zheng et al., our study adopted the perspective of geographic regions based on Trends. Earth recommended by UNCCD, analysing the geographical subdivisions of degraded areas in detail to establish a new multi-scale application of Trends.Earth.

Dynamic monitoring of LD based on the LDN system is highly feasible, yet it faces challenges and limitations, particularly in optimising assessment methods and datasets. The distinct assessment indicators and coarse grading and classification of these indicators make it difficult to monitor LD at small scales. To enhance LDN research, several improvements could be made: 1) Enhance assessment methods by including diverse indicators to comprehensively reflect various aspects of LD, such as soil quality and water status. Incorporating local geographical characteristics into indicator selection ensures accurate reflection of LD status in different regions. 2) Strengthen research and development of regional datasets for land organic carbon indicators to ensure more accurate and reliable monitoring results at geographical scales. 3) Promote international cooperation, particularly in data sharing, standardising monitoring methods, and sharing best practices, to improve global understanding and management of LD.

5 Conclusions

In this study, we utilised the Trends.Earth cloud computing method, recommended by UNCCD, to monitor LD in Mongolia from 2015 to 2020. Additionally, we conducted a thorough analysis of SDG15.3.1 indicators at the regional level, offering a unique perspective and comprehensive assessment of recent LD in Mongolia. We observed an increase in LD areas, accounting for 12.11% of the total land area. Severe degradation of land productivity was evident in the southern desert and desert steppe regions, while land cover degradation was noted in the steppe, high mountain, and mountain taiga areas. SOC degradation occurred in zones adjacent to the mountain taiga, steppe, and desert steppe. Relative to the base period of 2001–2015, the total land area showing improvement from 2015 to 2020 surpassed the area exhibiting degradation, indicating progress toward achieving the LDN target. However, LD persists in certain regions of Mongolia, particularly in the desert and desert steppe areas in the southwest and continues to encroach upon the steppe regions.

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地理分区视角下的蒙古国土地退化量化分析

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摘　要：自然和人为因素的干扰加速了干旱、半干旱和亚湿润干旱地区的土地退化（LD）过程，导致土地质量和生产力降低、生物多样性丧失、生态系统服务功能退化，乃至当地人民生活质量下降。为了防止土地退化，联合国防治荒漠化公约（UNCCD）提出土地退化零增长（LDN）目标。然而，由于缺少一致性评估的定量方法和工具，很难对全球或区域土地退化状态进行量化和对比研究。本研究尝试利用 UNCCD 推荐的 Trends.Earth 工具，选择土地退化问题突出的蒙古国为研究区，引入地理分区视角，研究其 2015–2020 年土地退化的格局与变化。主要结果如下：（1）总体上，2015–2020 年有 12.11%的地区新增加了土地退化，退化区域位于西南部荒漠、荒漠草原，并逐渐向东北部草原地理分区蔓延。（2）土地生产力指标恢复和退化区域分别为 17.62%和 11.79%，严重退化区域位于蒙古国南部荒漠和荒漠草原地理分区。（3）土地覆盖指标恢复和退化区域分别为 1.80%和 0.16%，退化区零散地分布在草原、高山和山地针叶林地理分区。（4）土地有机碳指标恢复和退化区域分别为 1.54%和 0.22%，退化区主要位于山地针叶林、草原与荒漠草原相邻地带。（5）LDN 综合指标恢复区面积（2.999×10^5 km^2）大于退化区面积（1.895×10^5 km^2），反映出土地退化零增长目标有向好趋势。

关键词：地理分区；土地退化；土地退化零增长；蒙古国；Trends.Earth