Chin. Geogra. Sci. 2024 Vol. 34 No. 1 pp. 67−78
https://doi.org/10.1007/s11769-023-1404-7

Springer Science Press
www.springerlink.com/content/1002-0063

# Effects of Enclosure on Grassland Ecological and Economic Benefits in Northern China

HU Bo[1, 2], WEN Qingke[1], XI Fengjiang[3], LI Mengyao[4], WANG Libing[5], REN Yuejuan[6]

(1. *Aerospace Information Research Institute*, *Chinese Academy of Sciences*, *Beijing* 100094, *China*; 2. *University of Chinese Academy of Sciences*, *Beijing* 100049, *China*; 3. *Inner Mongolia Remote Sensing Center Co.*, *Ltd.*, *Huhhot* 010000, *China*; 4. *Xilinhot the Maodeng pasture*, *Xilinhot* 026000, *China*; 5. *China University of Mining and Technology*, *Xuzhou* 221116, *China*; 6. *Shanxi Provincial Key Lab of Resources*, *Environment and Disaster Monitoring*, *Coal Geological Geophysical Exploration Surveying & Mapping Institute of Shanxi Province*, *Jinzhong* 030600, *China*)

**Abstract:** Grasslands in northern China serve the country as both an ecological barrier and a livestock production base. There, installing enclosures has been becoming the major grassland restoration measure adopted by many local governments. However, the effects of restoration on both ecological and production benefits of grassland remain unclear for implemented grassland restoration policies. Therefore, a representative rangeland in northern China, the Maodeng pasture in Inner Mongolia Autonomous Region was selected as the study area, and remote sensing monitoring analyses were carried out to quantify the ecological benefits and economic benefits from 2015 to 2021. The results showed that: 1) in terms of ecological benefits, the grassland area with a grassland coverage rate of more than 60% accounts for 32.3% of the regional area, and 86.4% of its grassland grew significantly better than the same period in 2015, showing a significant improvement in grassland growth. Using the average amount of carbon per unit area as the ecological benefit evaluation index, it increased by 27.1% to 32.48Tg C/yr from 2015 to 2021. 2) In terms of economic benefits, both theoretical grass production and livestock carrying capacity increased from 2015 to 2021. Compared to 2015, the theoretical grass production in 2021 increased by 24.8% to 71 900 t. The livestock carrying capacity reached 52 100 sheep units in 2021, nearly 11 000 sheep units more than that in 2015. During the study period, multiple economic indicators (on a per capita basis of permanent residents) for the pastoral area of Xilinhot City to which the Maodeng pasture belongs, have grown steadily. Per capita total income rose from 29 630 yuan (RMB) in 2015 to 62 859 yuan (RMB) in 2021. Relying on grassland resources to develop the pastoral ecology also broadens the potential economic development space. Overall, the establishment of the reserve and the experiment of implanting an enclosure policy have had a significant and positive impact on Maodeng pasture's development from both an ecological and economic perspective. With the support of scientific evidence, enclosure policy can be extended to more than 110 000 km$^2$ of grasslands in northern China with similar precipitation and temperature conditions, enhancing the productive and ecological potential of grasslands. The above research results will contribute to the scientific formulation of grassland pasture quality improvement plans in northern China.

**Keywords:** enclosure; grassland; ecological benefit; economic benefit; Maodeng pasture; Inner Mongolia; northern China

**Citation:** HU Bo, WEN Qingke, XI Fengjiang, LI Mengyao, WANG Libing, REN Yuejuan, 2024. Effects of Enclosure on Grassland Ecological and Economic Benefits in Northern China. *Chinese Geographical Science*, 34(1): 67−78. https://doi.org/10.1007/s11769-023-1404-7

Received date: 2023-04-24; accepted date: 2023-08-20

Foundation item: Under the auspices of the Inner Mongolia Autonomous Region Science and Technology Achievement Transformation Special Project (No. 2020CG0123), the Strategic Priority Research Program of Chinese Academy of Sciences (No. XDA26050301-01)

Corresponding author: WEN Qingke. E-mail: wenqk@aircas.ac.cn

## 1 Introduction

China is a country with abundant grassland resources, with an area of approximately 392.8 million ha, accounting for 40.9% of the country's land area (https://www.forestry.gov.cn/main/5462/20210311/115701724435306.html). Grassland plays an important role in ecological protection, which is specifically reflected in aspects such as conserving water sources, maintaining soil and water, preventing wind and sand, and protecting biodiversity (Zhao et al., 2020). At the same time, grassland can provide forage and food, and is an important livestock production base (Bai et al., 2020). How to handle and coordinate the relationship between grassland protection and utilization is a difficult and urgent issue in the near decades. Therefore, it is imperative to find a feasible and cost-effective grassland protection manner. In order to scientifically protect grassland, China has implemented a variety of grassland protection policies, including the establishment of national grassland natural parks and enclosures. Enclosure (Meissner and Facelli, 1999) as a grassland management method is a way for humans to consciously adjust the relationship between herbivores and plants in the grassland ecosystem and to better manage the grassland. Grassland enclosures divide the grassland into several small areas, so that the enclosed degraded grassland can recover naturally due to the elimination of livestock pressure (Yan et al., 2009). Enclosure mainly serves to artificially reduce or completely eliminate the impact of livestock on the grassland ecosystem (Zuo et al., 2009), so the latter can recover and rebuild under its own elasticity (Li, 1995). There is an urgent need for scientific evaluation of the effectiveness of the enclosure policy.

Grassland is of great ecological importance. As a key component of the ecosystem, it plays an important role in water protection (Li et al., 2022), soil conservation (Liu et al., 2022), carbon storage (Ni, 2002) and biodiversity maintenance. Research showed that an effective grassland management and conservation practices can improve water quality, reduce soil profile (Li et al., 2018), and promote plant and animal diversity in grasslands (Tilman and Downing, 1994). Due to the large extent of grasslands (Ali et al., 2016), understanding its dynamics through field surveys requires a lot of manpower and material resources. Accordingly, there has been much research into remote sensing as an economical and convenient means of monitoring grassland (Shen et al., 2016). These studies have focused on various grassland parameters, such as biomass, habitat identification (Fazzini et al., 2021), leaf area moisture (Sibanda et al., 2021) and grass production (Vallentin et al., 2022). The role and value of grasslands in carbon storage is often underestimated. Efforts to mitigate climate change tend to prioritize carbon stored in trees over carbon stored in grasslands (Xu et al., 2007). Grasslands have great potential to increase carbon stocks through improved grassland use or management (Wang et al., 2021). Therefore, the assessment of grassland carbon storage is also very important.

Grasslands are also rich in economic benefits, such as pasture production (Vuffray et al., 2017), animal husbandry (Zhang et al., 2019), tourism (Parente and Bovolenta, 2012) and bioenergy production (Machovina and Feeley, 2017). With the rapid development of China's livestock industry, the shortfall in grass resources is a very large amount (Qi, 2014) . In terms of forage alone, it has been relying on imported high-quality forage from abroad for many years. China's grassland area is vast, but the proportion of high-quality grassland is actually low. The shortage of quality forage for grass-fed livestock in China is a pressing problem that needs to be solved soon, being a more urgent one for the whole Inner Mongolia Autonomous Region. Over the past few decades, agriculture and animal husbandry have been important economic pillars in many regions (Zhang and Zhang, 2022), and the sustainable management and rational use of grasslands have played a key role in the development of agriculture and animal husbandry. In recent years, an increasing number of studies have measured and evaluated the benefits of grassland (Gorelick et al., 2017), with many evaluation methods applied. But one problem is that most studies have many indicators but a single research perspective. In actual evaluation, it is necessary to conduct a multivariate analysis of the grassland economy from ecological perspectives such as livestock carrying capacity and grass production, as well as from statistical perspectives such as GDP (Gross Domestic Product) and CDI (Capital Disposable Income).

The improvement of ecological benefits will promote the realization of carbon neutrality and carbon peak goals. The pastoral economy relying on grassland resources will also expand the space for economic development. In order to achieve the goal of regional high-quality development in which grassland ecology and economy are coordinated, this paper selects the grassland enclosure of the Maodeng pasture, a representative grassland in northern China, and conducts a multi-index evaluation of the enclosure benefits from both ecological and economic benefits. Through comparative analysis before and after the implementation of the enclosure policy, the benefits of the enclosure policy are quantitatively clarified with empirical evidence. This research will provide high-quality development methods for more grasslands in northern China.

## 2 Study Area

Maodeng pasture is located in the central part of the Xilin Gol League and the northeastern part of Xilinhot City, Inner Mongolia Autonomous Region in China (Fig. 1). It is a typical representative grassland in northern China. It has a temperate dry continental climate, with annual average temperature of 0.5°C to 1.0°C, and average annual precipitation of 300 to 360 mm which mostly concentrated in June to August. It is dominated by low hills and flat areas. This area is suitable for feed crops such as wheat, with rich vegetation resources and high nutritional value (Wang et al., 2022).

As an important livestock production base in China, the Maodeng pasture is not only an excellent agricultural demonstration area, but also an important natural ecological barrier with a valuable ecological buffer function. In 2014, General Secretary Xi Jinping personally visited the Maodeng pasture and put forward requirements to improve the pasture's ecology and economic level. To realize those requirements and expectations, in recent years, Maodeng pasture has cleared the non-herdsmen within the rangeland of this pasture, cleared it for enclosure, initially built an ecological protection area, and then managed and protected this restoration area.

## 3 Data and Methods

### 3.1 Data sources and preprocessing

#### *3.1.1 Remote sensing data*

Landsat 8 satellite data were used to assess the interannual grassland status of the Maodeng pasture. The Landsat 8 Level 2, Collection 2 dataset containing atmospherically corrected surface reflectance were obtained using GEE (Google Earth Engine) platform (Xu and Tang, 2013). After cloud removal and other preprocessing, the average NDVI (Normalized Difference Vegetation Index) of all the images in the annual peak growth season (July–September) was calculated as the annual NDVI from 2015 to 2021.

Sentinel-2 data were used to extract grassland areas and conduct monthly grassland growth status monitoring. The Sentinel-2 atmospheric apparent reflectance product after orthorectification and sub-pixel level geo-

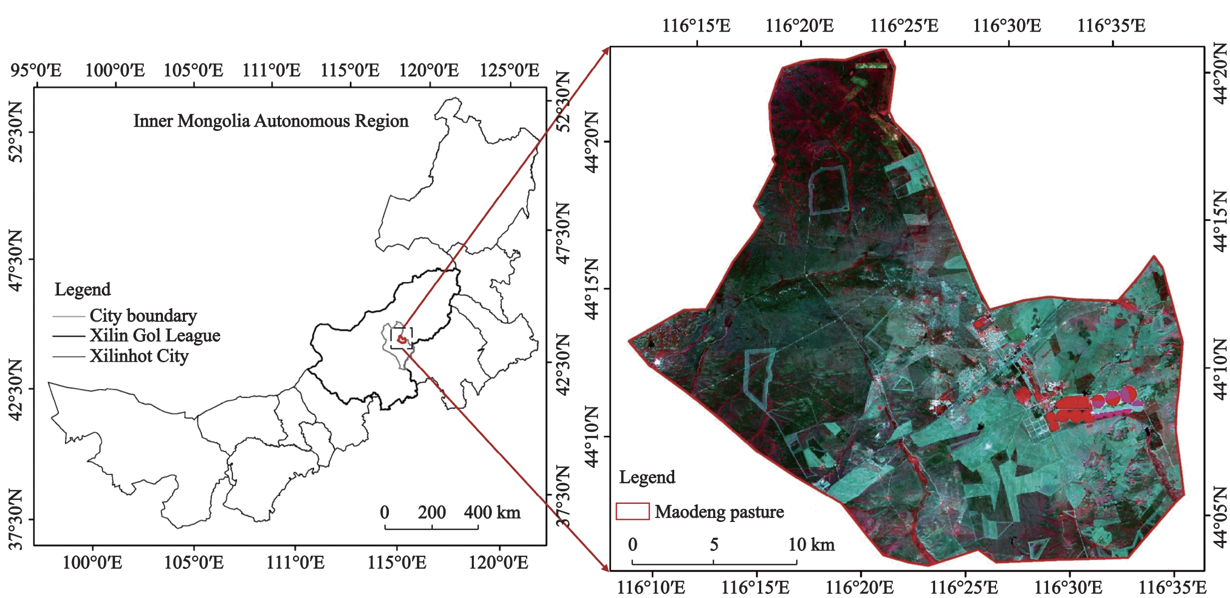


**Fig. 1** Location of Maodeng pasture in northern China (Remote sensing image data source: Sentinel-2; time: August 30, 2021)

metric precision correction was downloaded from the USGS (United States Geological Survey) platform (Tian et al., 2019). Data preprocessing includes radiometric calibration, atmospheric correction, cloud removal, splicing, *etc*. The image on August 30, 2021 was used to extract the grassland range. In order to obtain the peak growing season of grassland, the average NDVI value of each month was calculated based on the GEE platform for all the preprocessed data in 2020.

#### *3.1.2 Meteorological data*

Temperature and precipitation data were obtained from the National Meteorological Science Data Center (http://www.nmic.cn/site/index.html). Data from the Xilinhot site were selected to analyze the effects of temperature and precipitation on the grass growth conditions of Maodeng pasture. The Climatic Research Unit gridded Time Series (CRU TS) climate dataset produced by National Centre for Atmospheric Science (NCAS) were used to determine the extent of areas with similar hydrothermal conditions to those at Maodeng pasture.

#### *3.1.3 Statistical data*

To analyze the economic impact of the enclosure policy on the Maodeng pasture, data indicators from 2015 to 2021 were obtained from Xilin Gol League Statistical Yearbook (Xilin Gol League Statistical Bureau, 2016–2022). Statistics included the per capita total income, disposable income and per capita total expenditure of permanent residents in the pastoral area of Xilinhot City from 2015 to 2021. Among them, due to changes in yearbook statistics in 2020 and 2021, the values of permanent residents in agricultural and pastoral areas are used.

#### *3.1.4 Validation data*

To verify the accuracy of the classification results, a field visit to Maodeng pasture was conducted in September 2021. GVG software was used to record the types of ground objects at 34 points in the study area.

### 3.2 Methodology

This study began with the identification of grassland distribution areas in the Maodeng pasture, to obtain information where and how its grassland is used. The temporal change in NDVI values was calculated by selecting images from different years; this time-series data was also used to evaluate grassland growth status and the occurrence of grassland degradation in the Maodeng pasture. The time-series variation in the carbon sink was estimated by combining meteorological data, ground data, and data on the pasture's plant and animal types. Grassland yield estimation is the basis of grass-livestock balance accounting, and the level of grass yield is a key indicator of grassland health. Based on the relationship between NDVI and grass production in different areas, the theoretical grass production in the study area was estimated. The calculated theoretical livestock carrying capacity of the pasture was based on the theoretical livestock carrying capacity model. The research framework of this study is as follows (Fig. 2).

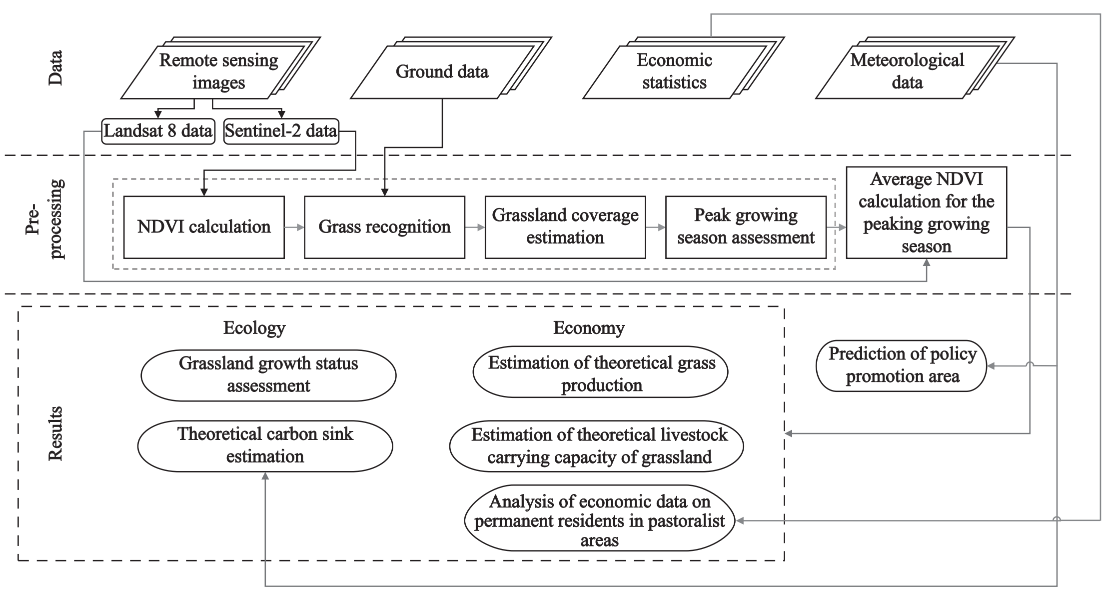


**Fig. 2** Research framework diagram of this study (NDVI: Normalized Difference Vegetation Index)

#### *3.2.1 Grassland growth state assessment*

The normalized vegetation index was used to characterize the growth state of grassland. First of all, it is necessary to identify the grassland distribution area through the classification of the land use types. According to the actual situation of the study area, the decision tree model was used to divide the land use types in the study area into four categories: grassland, cultivated land, water, and building. The grassland distribution areas were extracted for subsequent research. NDVI is calculated as follows:

$$NDVI = \frac{B_{NIR} - B_R}{B_{NIR} + B_R} \tag{1}$$

where $B_{NIR}$ and $B_R$ denote the represent the Digital Number (DN) value of the red and near infrared bands of the image respectively.

#### *3.2.2 Evaluating grassland growth improvement and degradation*

Applying a trend analysis at the pixel scale using long time-series data can reveal a general trend of the data, and this method has been used extensively in studies addressing similar management issues for grasslands (Yin et al., 2020). A tendency rate > 0 means that a grassland's growth is improved, whereas a rate < 0 indicates its degradation.

Comparing images from the same time period can provide information on dynamics (changes in the growth) of grassland vegetation over time, and also whether the grass is growing well or not (degrading). Data difference is a quick and easy way to evaluate grassland degradation (Zhou et al., 2017). This is done by arithmetically subtracting the NDVI values of two images taken at the same time phase on different dates; a resulting value > 0 indicates good growth whereas a value < 0 implies degradation at a given time. We used these thresholds to classify restoration levels into four categories: difference ≤ –0.15, severely degraded areas; –0.15 < difference ≤ 0, generally degraded areas; 0 < difference ≤ 0.15, generally improved areas; difference > 0.15, significantly improved areas.

#### *3.2.3 Estimating theoretical carbon sinks*

By establishing the relationship between NDVI and aboveground biomass, the aboveground biomass and its spatiotemporal changes were calculated (Fang et al., 2007) Above-ground biomass of grassland (*Y*) can be calculated by the following formula：

$$Y = 179.71 \times NDVI_{\mathrm{MAX}}^{1.6228} \ (R^2 = 0.71,\ P < 0.0001) \tag{2}$$

$NDVI_{\mathrm{MAX}}$ refers to the maximum NDVI of this year at each spatial location. Next, the resulting biomass estimate was converted into carbon (conversion factor: 0.45) based on the average grass production per unit area of each grassland type in every province as recorded in the Grassland Resource Data of China (http://www.forestdata.cn/) and following the method proposed by Fang et al. (2007).

#### *3.2.4 Estimating theoretical grass production*

Considering the geographical location of the Maodeng pasture, along with the research by Cao et al. (2019), grass production and NDVI in the Xilin Gol League sample were related as follow:

$$Y = \mathrm{e}^{(3.46-(0.539/NDVI))} \tag{3}$$

where *Y* is the empirical model simulation value of grass yield, in 10 g/m$^2$.

$$Y_{\mathrm{IN}} = D_{\mathrm{pixel}}{}^2 \times Y/10 \tag{4}$$

In the above equation, $Y_{\mathrm{IN}}$ is the fresh grass yield (g) for each pixel range applicable to the local grassland area of the Xilin Gol League; $D_{\mathrm{pixel}}$ is the spatial resolution of the fresh grass yield raster data (m).

#### *3.2.5 Estimating the theoretical livestock carrying capacity of grassland*

The theoretical livestock carrying capacity of the study area was estimated using the Regional Grassland Total Reasonable Year-Round Livestock Carrying Capacity model (Xu, 2014). Accoriding to the *NY/T 635-2015 Agricultural Industry Standard of the People's Republic of China: Calculation of Reasonable Livestock Carrying Capacity of Natural Grassland*, total reasonable livestock carrying capacity of regional grassland in a year and in different utilization periods was calculated. The amount of available standard hay and the standard hay conversion coefficient by grassland type; the reasonable utilization rate of grassland according to grassland type; and the edible forage yields. Below is the formula for calculating the total reasonable annual livestock carrying capacity of grassland (in the push-back area):

$$A = \frac{(Y \times S) \times (1+G) \times U \times H}{I \times 365} \tag{5}$$

where *A* is the total reasonable yearly livestock carrying capacity of all grassland areas (sheep units). *Y* is the unit edible forage yield per unit (g/m$^2$) at first bloom. *S* is the entire area of grassland ($m^2$). $G$ is the forage regeneration rate (%), which is taken as 15% in this study. $U$ is the reasonable utilization rate of grassland (%), which is taken as 50% here; $H$ is the standard hay conversion factor for grassland, which is taken as 1.00; $I$ is the daily diet of one sheep unit, the latter having a value of 1800 g/d.

## 4 Results and Analyses

### 4.1 Changes in ecological benefits of Maodeng pasture from 2015 to 2021

In 2021, grassland cover of the Maodeng pasture amounted to 548.8 $km^2$, this accounting for 93.8% of the total area of the site (Fig. 3). Totally, the grassland area with a grassland coverage rate of more than 60% accounts for 32.3% of the regional area. while for just over two-thirds (67.2%) of the pasture the grassland coverage rate was between 20% and 60%. Notably, grassland coverage rate below 20% was limited to just 0.5% of the studied area.

Through monthly monitoring of grassland growth conditions in the study area in 2020, it was determined that the peak growing season of the grassland in Maodeng pasture is from July to September. Using the Landsat 8 data, based on the GEE platform, the annual plot of NDVI average during peak growing season of the Maodeng pasture from 2015 to 2021 was obtained (Fig. 4). The results showed that the growth status of grassland was changing with time. In the northwest, grassland growth was worse than in the southeast before 2017, but has improved significantly since then. The grassland in the northern part of the eastern reclamation area showed obvious degradation from 2015 to 2017, and began to improve after 2020. The growth of grassland in the western region is getting better and better.

To scientifically reveal the changes in grassland growth at the Maodeng pasture in recent years, two periods of highly comparable monitoring data were selected for comparison (i.e., two periods spanning six year with identical monitoring dates on 28 July 2015 and 28 July 2021) (Fig. 5). The results of comparing the grassland's dynamics between 2015 and 2021 were divided into four categories: significantly degraded area, general degraded area, general improvement area, and significant improvement area, using the thresholds of –0.15, 0, and 0.15.

The results showed a clear trend of improved growth of grassland in the Maodeng pasture overall, with 86.4% of the pasture area in 2021 was significantly improved than that in 2015; the remaining 13.6% of grassland is in a degraded state, of which 13.1% is general degraded. This revealed that significantly improvement area in

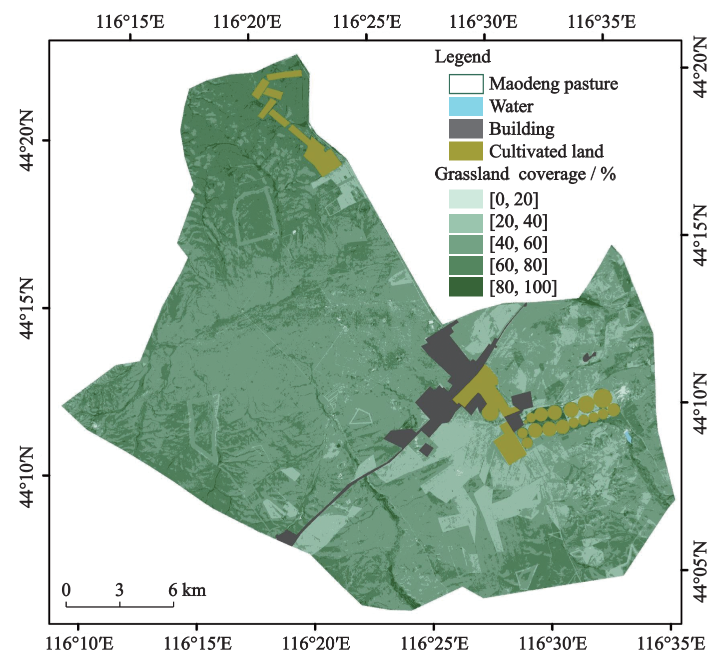


**Fig. 3** Grassland's distribution and cover status for the Maodeng pasture of northern China in 2021

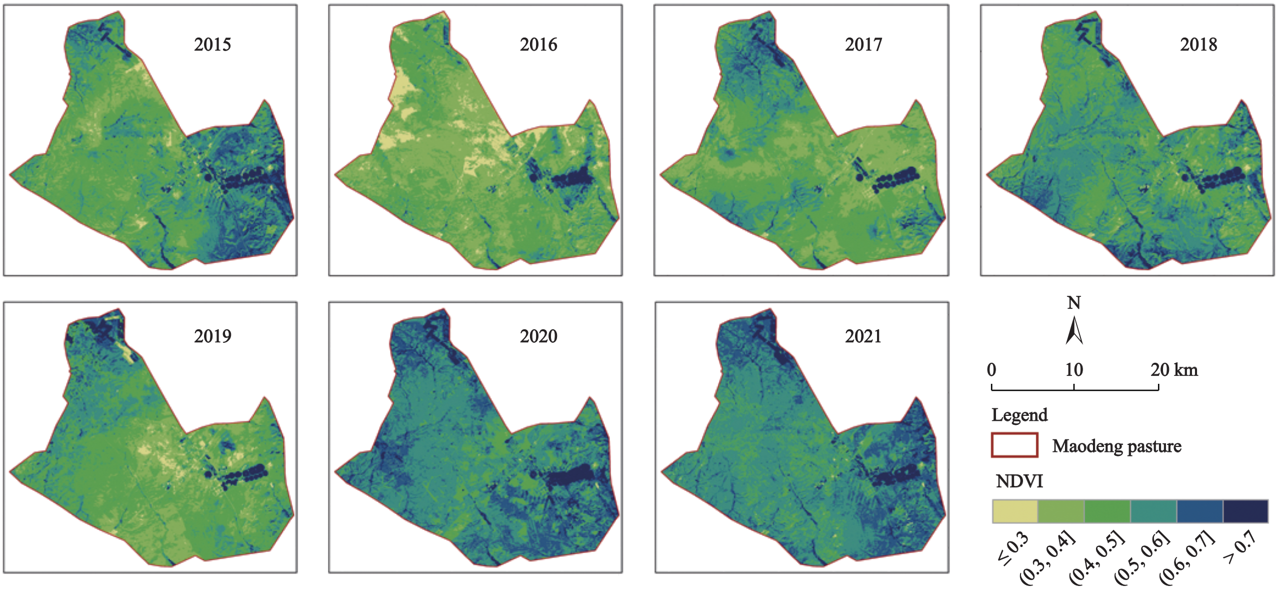


**Fig. 4** Annual plot of NDVI average during peak growing season (July to September) of the Maodeng pasture in northern China from 2015 to 2021

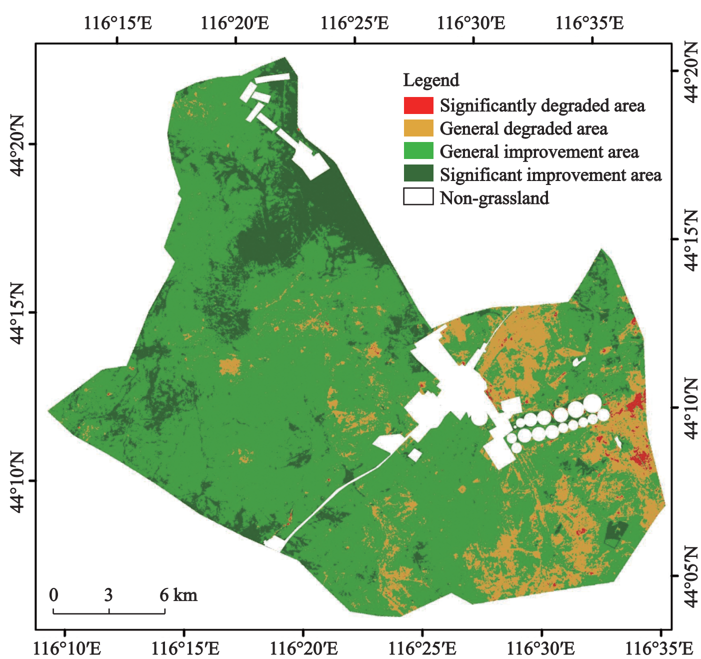


**Fig. 5** Change of grassland growth status in Maodeng pasture in northern China from 2015 to 2021

Maodeng pasture totaled 77.7 km$^2$, accounting for 14.2% of the entire grassland area; general improvement area totaled 396.4 km$^2$, accounting for most (72.2%) of the entire grassland area; the general degraded area totaled 72.3 km$^2$ and the significantly degraded area totaled 2.3 km$^2$, respectively 13.2% and 0.4% of the entire grassland area.

The grassland biomass was calculated based on the average NDVI value of the annual peak growing season (July to September) of Maodeng pasture from 2015 to 2021. Then converted it to the annual average carbon per unit of grassland area (Fig. 6). During the six years, although the average changes in carbon per unit area content fluctuated, it showed a steady increase in the overall state. This value reached its maximum in 2020, with 33.41 Tg C/yr. It in 2021 compared to the same period in 2015 has an increase of 27.10%.

The differences in local carbon sink at each location

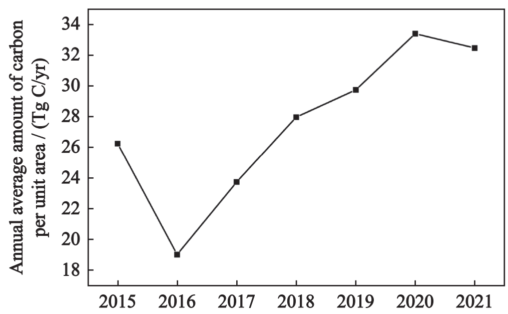


**Fig. 6** Annual average changes of carbon per unit area in Maodeng pasture of northern China from 2015 to 2021

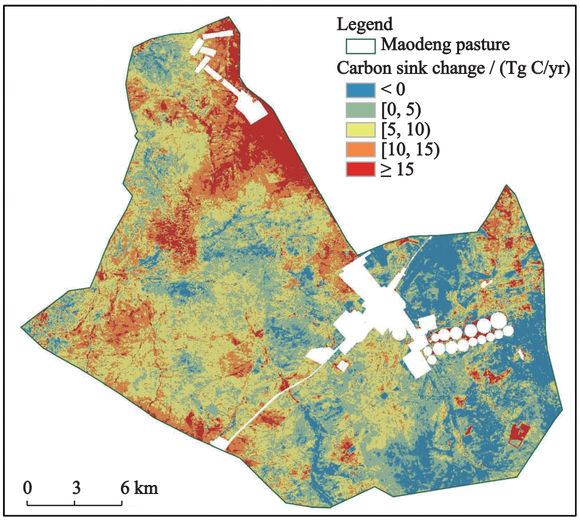


**Fig. 7** Distribution of carbon sink changes of Maodeng pasture in northern China from 2021 to 2015

within the Maodeng pasture for the same observation time in 2015 and 2021was calculated (Fig. 7). Overall, the average carbon sink in 2021 has increased by 27.10% compared to the same period in 2015. The localized analysis revealed a partial reduction in the carbon sink within the eastern part of the Maodeng pasture, particularly those adjacent to built-up and cultivated places, but this reduction is not significant. By contrast, a significant and noticeable increase in the carbon sink has occurred within the protected area in the northwestern part of the Maodeng pasture. The significant increase in the carbon sink of pasture contributes significantly to the goals of carbon neutrality and carbon peaking.

## 4.2 Changes in economic benefits of Maodeng pasture

Theoretical grass production was estimated for 2015 and 2021 by a theoretical grass production model (Fig. 8). These results excluded areas of the Maodeng pasture where grass vegetation could not grow (i.e., cultivated land, water, and building).

Estimates show that average grass production in 2015 was about 105 g/m$^2$, with a yield of about 57 600 t. In 2021 it will be 131 g/m$^2$, with a yield of about 71 900 t. Compared with 2015, the theoretical grass production of the Maodeng pasture in 2021 increased by 14 300 t, an increase of 24.83%. The shortage of quality forage for grass-fed livestock in China is a pressing problem that needs to be solved soon, being a more urgent one for the whole Inner Mongolia Autonomous Region. The results show that the amount of grass produced in enclosure pastures can increase in just a few years, indicating that its economic benefits are obvious and its social and economic development potential is huge.

Theoretical livestock capacity of Maodeng pasture in 2015 and 2021 were 41 800 sheep units and 52 100 sheep units, respectively, with an increase of 24.64%. More than 70% of the income of most herdsmen comes from animal husbandry. The rapid increase in livestock

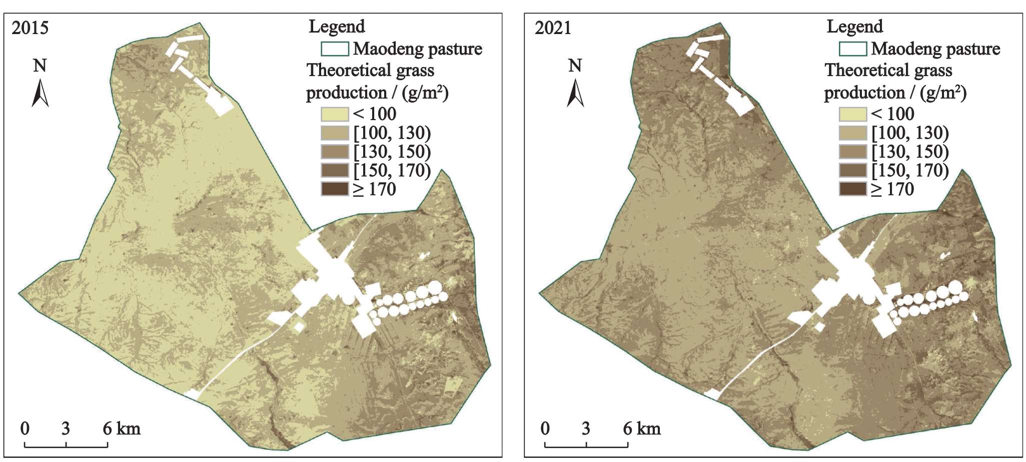


**Fig. 8** Distribution of theoretical grass production in the Maodeng pasture of northern China in 2015 and 2021

capacity will help herders increase their income and become rich.

Since there is no small-scale economic data for Maodeng pasture, we consulted the annual yearbook data published by the Xilin Gol League Statistics Bureau where Maodeng pasture is located (Fig. 9). Statistics obtained the per capita total income, disposable income and total expenditure of permanent residents in the pastoral area of Xilinhot City from 2015 to 2021. Among them, due to changes in yearbook statistics in 2020 and 2021, the values of permanent residents in agricultural and pastoral areas are used.

These results show that, from 2015 to 2021, both per capita total income and total expenditure of the permanent pastoral residents of Xilinhot City, to which the Maodeng pasture belongs, have steadily risen. The per capita total income which has doubled from 29 630 to 62 859 yuan (RMB). Per capita disposable income can be used to measure people's living standards and purchasing power. It has increased from 19 036 to 30 232 yuan (RMB) in six year. Per capita total expenditure is a direct factor driving economic growth. It has increased from 35 427 to 47 429 yuan (RMB). This is an important indicator that reflects the effective improvement of residents' living standards and quality. Evidently, their lives have become better. This showed that enclosing the Maodeng pasture has not only not impacted the economic life of its herders but also brought about higher economic growth.

## 5 Discussion

### 5.1 Significance of enclosures for grassland

Compared with other studies, we take the Maodeng pasture, a typical pasture in northern China that has implemented the enclosure policy, as the research area, and it is of great significance to carry out remote sensing monitoring on an annual scale. In addition, the ecological benefits and economic benefits are organically combined, and the impact is evaluated in a comprehensive and multi-level manner. Under the policy of enclosure, the Maodeng pasture has generally developed well over a 6-year span, with a high rate of development and huge economic benefits. These ecological benefits have improved and progressed significantly, also being a direct outcome of enclosure and sealing off of degraded grassland, which is of great significance to grassland resource management. On the one hand, the carbon sink of the pasture has also increased significantly, on average, which great contributes to the goal of carbon neutrality and attaining peak carbon. On the other hand, relying on grassland resources to develop the pastoral economy also has broadened the potential economic development space.

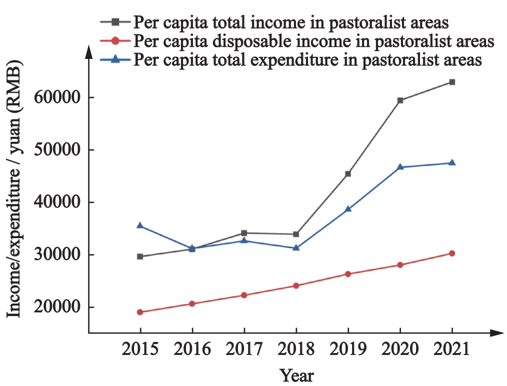


**Fig. 9** Changes in economic data on permanent residents in pastoralist areas in Xilinhot City from 2015 to 2021

With the rapid development of China's livestock industry, the shortfall in grass resources is a very large amount, from the forage alone an aspect, for many years rely on the import of foreign high-quality forage. The country has a large expanse of grassland, but its proportion of high-quality grassland is actually low. There are certain inherent limitations to their future development and utilization. The shortage of quality forage for grass-fed livestock in China is a pressing problem that needs to be solved soon, being a more urgent one for the whole Inner Mongolia Autonomous Region. Our results show that the amount of grass produced in enclosure pastures can increase in just a few years, with obvious economic benefits and great potential for socioeconomic development. Currently, the enclosure effect on the Maodeng pasture is steadily improving. From the perspective of economic efficiency and the economic utilization rate, multi-year grazing ban areas could be considered for light grazing with grass-fed livestock combined production methods, so to improve the net economic efficiency of grass resources and their utilization rate.

### 5.2 Promotion of policies

It is valuable to summarize replicable models and experiences for the ecological restoration and management of typical grasslands via the transformation and use of scientific and technological achievements and the active participation of herders, so that the ecological, economic, and social benefits of expanded grassland pastures can be significantly improved. The CRU TS climate dataset produced by the NCAS in the UK were used here to analyze those areas with similar temperature and precipitation conditions to the Maodeng pasture. From that, Globeland30 (Global LandCover, GLC) product with 30-m resolution were used to select areas of grassland where the Maodeng pasture enclosure policy could be replicated, as shown in Fig. 10 below.

From the perspective of hydrothermal conditions, there are more than 110 000 $km^2$ of grassland in the northern and central regions of Inner Mongolia Autonomous Region and conditions similar to Maodeng pasture. Those pastures can learn from the more mature enclosure model experiment of the Maodeng pasture, starting from the current situation of natural grasslands, with the following objectives: promoting the sustainable development of grassland ecology; protecting and restoring grassland vegetation, as the core; improving the grassland ecological environment; increasing the income of farmers and herders, as the goal; and accelerating the degraded grassland The overarching aim is to improve the grassland ecological environment while increasing the income of farmers and herders, and to accelerate the restoration and treatment of degraded grassland ecosystems.

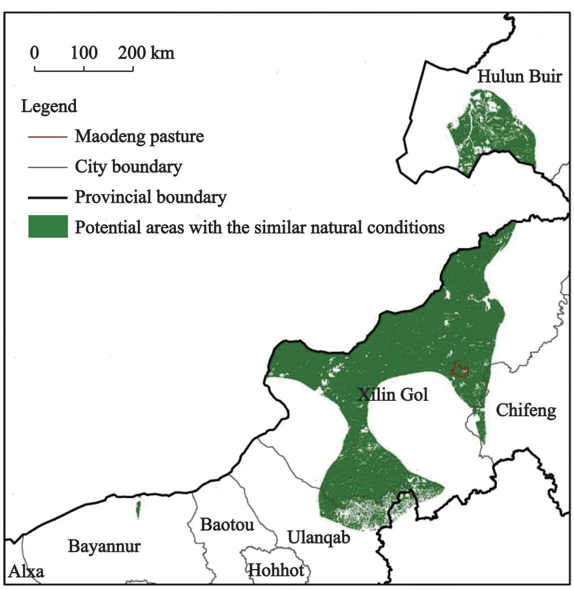


**Fig. 10** Potential areas with the similar natural conditions to improve grassland quality using the Maodeng pasture management model

### 5.3 Deficiencies and limitations

Due to various practical factors, there are still some uncertainties in the data and methods used in this paper. Such as the uncertainty of the model, the uncertainty of the selection of satellite remote sensing data, and the uncertainty of the statistical yearbook data. These all have more or less influence on the results. For example, changes in grassland growth conditions are not solely caused by the implementation of enclosure policies, but also influenced by many factors, such as temperature and precipitation.

In future large-scale research, the influence of multiple factors needs to be integrated. In terms of the value and calculation of the carbon sink, although the method we adopted a fitting algorithm commonly used in recent years, it is only suitable for coarse estimation over a small area like the Maodeng pasture. Therefore, it is slightly inadequate in terms of accuracy and scalability. Further, given the lack of continuous economic data specific to the studied ranch site, the economic data of permanent residents in the pastoral area of Xilinhot City, to which the Maodeng pasture belongs, is the most accurate economic indicator currently available. Accordingly, a unified comprehensive benefit evaluation index system and model are essential for evaluating the governance effect and to provide a robust reference for the governance and sustainable development of grasslands' animal husbandry.

## 6 Conclusions

In order to explore the impact of enclosure on achieving coordinated development of grassland ecology and economy, this study took the enclosure situation of typical pastures in northern China as the object, and evaluated the grassland enclosure policy in the study area from both ecological and economic aspects. The main findings are as follows. (1) Grassland enclosure is an important way of protecting grassland resources and plays a crucial role in the sustainable and efficient use of grassland resources in local pasture areas. Enclosure policy is effective and feasible in the short term. In 2021, the grassland area with a grassland coverage rate of more than 60% accounts for 32.3% of the regional area, grasslands with grassland coverage rate between 20% and 60% accounted for 67.2%, and only 0.5% had grassland coverage rate less than 20%. By assessing overall grassland growth in the Maodeng pasture from 2015 to 2021, its positive trend is evident. By quantitatively comparing the growth of grassland in 2015 with that in 2021, significantly improvement area in Maodeng pasture accounts for 14.2% of the entire grassland area; general improvement area accounts for 72.2%; the general degraded area and the significantly degraded area account 13.2% and 0.4% of the entire grassland area, respectively. The annual average carbon sink increased by 7.41 Tg C/yr per unit area compared to 2015, with wide scale increase.

(2) Economic benefits had also been greatly improved. Compared to 2015, theoretical grass production of the Maodeng pasture in 2021 increased by 14 300 t, while theoretical livestock capacity of Maodeng pasture in 2021 reached 52 100 sheep units, respectively, with an increase of 24.64%. Due to the implemented grass protection policy, statistics obtained the per capita total income, disposable income and total expenditure of permanent residents have steadily increased. The per capita total income even has doubled from 29 630 to 62 859 yuan (RMB).

(3) Overall, the study confirms that the establishment of the reserve and the experiment of implanting an enclosure policy have had a significant and positive impact on the Maodeng pasture's development. Therefore, we recommend promoting enclosure in a wider area with similar water and heat conditions as the presently studied protected area, so as to achieve a high-quality development path for grassland regions in northern China.

## Conflict of Interest

The authors have no competing interests to declare that are relevant to the content of this article.

## Author Contributions

All authors contributed to the study conception and design. HU Bo and WEN Qingke sorted out the context and direction of the article. The first draft of the manuscript was written by HU Bo and all authors commented on previous versions of the manuscript. XI Fengjiang and LI Mengyao provided important data for the study area. Material preparation, data collection and analysis were performed by WANG Libing and HU Bo. REN Yuejuan offered suggestions on some of the approaches. All authors read and approved the final manuscript.

## References

Ali I, Cawkwell F, Dwyer E et al., 2016. Satellite remote sensing of grasslands: from observation to management. *Journal of Plant Ecology*, 9(6): 649–671. doi: 10.1093/jpe/rtw005

Bai Yongfei, Zhao Yujin, Wang Yang et al., 2020. Assessment of ecosystem services and ecological regionalization of grasslands support establishment of ecological security barriers in Northern China. *Bulletin of the Chinese Academy of Science*, 35(6): 675–689. (in Chinese)

Cao Zhengqi, 2019. *Analysis of Spatiotemporal Characteristics of Grass Production and Grass-livestock Balance in Xilingol League from 2000 to 2017*. Huhhot: Inner Mongolia University. (in Chinese)

Fang J Y, Guo Z D, Piao S L et al., 2007. Terrestrial vegetation carbon sinks in China, 1981−2000. *Science in China Series D:Earth Sciences*, 50(9): 1341–1350. doi: 10.1007/s11430-007-0049-1

Fazzini P, De Felice Proia G, Adamo M et al., 2021. Sentinel-2 remote sensed image classification with patchwise trained ConvNets for grassland habitat discrimination. *Remote Sensing*, 13(12): 2276. doi: 10.3390/RS13122276

Gorelick N, Hancher M, Dixon M et al., 2017. Google Earth Engine: planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, 202: 18–27. doi: 10.1016/j.rse.2017.06.031XSA

Li C Y, Peng F, Xue X et al., 2018. Productivity and quality of alpine grassland vary with soil water availability under experimental warming. *Frontiers in Plant Science*, 9: 1790. doi: 10.3389/fpls.2018.01790

Li M H, Wang X Y, Chen J C, 2022. Assessment of grassland ecosystem services and analysis on its driving factors: a case study in Hulun Buir Grassland. *Frontiers in Ecology and Evolution*, 10: 841943. doi: 10.3389/fevo.2022.841943

Li Yonghong, 1995. Restoration dynamics of degraded grasslands in the typical steppe zone of Inner Mongolia. *Chinese Biodiversity*, 3(3): 125–130. (in Chinese)

Liu X Y, Lai Q, Yin S et al., 2022. Exploring grassland ecosystem water use efficiency using indicators of precipitation and soil moisture across the Mongolian Plateau. *Ecological Indicators*, 142: 109207. doi: 10.1016/J.ECOLIND.2022.109207

Machovina B, Feeley K J, 2017. Restoring low-input high-diversity grasslands as a potential global resource for biofuels. *Science of the Total Environment*, 609: 205–214. doi: 10.1016/j.scitotenv.2017.07.109

Meissner R A, Facelli J M, 1999. Effects of sheep exclusion on the soil seed bank and annual vegetation in chenopod shrublands of South Australia. *Journal of Arid Environments*, 42(2): 117–128. doi: 10.1006/jare.1999.0515

Ni J, 2002. Carbon storage in grasslands of China. *Journal of Arid Environments*, 50(2): 205–218. doi: 10.1006/jare.2001.0902

Parente G, Bovolenta S, 2012. The role of grassland in rural tourism and recreation in Europe. In: *Grassland: A European Resource? Proceedings of the 24th General Meeting of the European Grassland Federation*. Lublin, Poland: Polish Grassland Society, 733–743.

Qi Te, 2014. *Protection and Economic Utilization of Grassland Resources under Enclosure and Grazing Policy-A Study of Xilamule Grassland in Baotou*. Huhhot: Inner Mongolia University. (in Chinese)

Shen Haihua, Zhu Yankun, Zhao Xia et al., 2016. Analysis of current grassland resources in China. *Chinese Science Bulletin*, 61(2): 139–154. (in Chinese)

Sibanda M, Onisimo M, Dube T et al., 2021. Quantitative assessment of grassland foliar moisture parameters as an inference on rangeland condition in the mesic rangelands of southern Africa. *International Journal of Remote Sensing*, 42(4): 1474–1491. doi: 10.1080/01431161.2020.1832282

Tian Ying, Chen Zhuoqi, Hui Fengming et al., 2019. Analysis of data characteristics and application prospects of ESA Sentinel satellite Sentinel-2A/B. *Journal of Beijing Normal University (Natural Science)*, 55(1): 57–65. (in Chinese)

Tilman D, Downing J A, 1994. Biodiversity and stability in grasslands. *Nature*, 367(6461): 363–365. doi: 10.1038/367363a0

Vallentin C, Harfenmeister K, Itzerott S et al., 2022. Suitability of satellite remote sensing data for yield estimation in northeast Germany. *Precision Agriculture*, 23(1): 52–82. doi: 10.1007/s11119-021-09827-6

Vuffray Z, Deleglise C, Schori F et al., 2017. Typology of the production of pastures. *Agrarforschung Schweiz*, 8(11−12): 428–437.

Wang Le, Dong Lei, Hu Tianyu et al., 2021. History and prospect of vegetation map compilation in China. *Science in China (Series C)*, 51(3): 219–28. (in Chinese)

Wang Yu, Jia Yushan, Bao Jian et al., 2022. Effects of different fertility periods and slope positions on forage yield and quality in typical grassland hills of Maodeng pasture. *Heilongjiang Animal Science and Veterinary Medicine*, (1): 1–8. (in Chinese)

Xilin Gol League Statistics Bureau, 2016–2022. *Statistical Yearbook of Xilin Gol League*. Beijing: China Statistics Press, 429-431; 310-311; 2(22-67); 271-277;396-398; 381-385; 356-360. 429–431, 310–311, 2(22–67), 271–277, 396–398, 381–385, 356–360.

Xu Hanqiu, Tang Fei, 2013. New generation of Landsat series satellites: new features and ecological implications of Landsat 8 remote sensing images. *Acta Ecologica Sinica*, 33(11): 3249–3257. (in Chinese)

Xu Minyun, 2014. A review of grassland carrying capacity: perspective and dilemma for research in China on ‘forage-livestock balance’. *Journal of Pratacultural Science*, (5): 321–329. (in Chinese)

Xu Xiaofeng, Tian Hanqin, Wan Shiqiang, 2007. Climate warming impacts on carbon cycling in terrestrial ecosystems. *Journal of Plant Ecology*, 31(2): 175–188. (in Chinese)

Yan Yuchun, Tang Haiping, Xin Xiaoping et al., 2009. Advances in research on the effects of exclosure on grasslands. *Acta Ecologica Sinica*, 29(9): 5039–5046. (in Chinese)

Yin L C, Feng X M, Fu B J et al., 2020. Irrigation water consumption of irrigated cropland and its dominant factor in China from 1982 to 2015. *Advances in Water Resources*, 143: 103661. doi: 10.1016/j.advwatres.2020.103661

Zhang J P, Zhang L B, Liu X N et al., 2019. Research on sustainable development in an alpine pastoral area based on equilibrium analysis between the grassland yield, livestock carrying capacity, and animal husbandry population. *Sustainability*, 11(17): 4659. doi: 10.3390/su11174659

Zhang X, Zhang X L, 2022. Total factor productivity of herdsmen animal husbandry in pastoral areas: regional differences and driving factors. *Sustainability*, 14(22): 15347. doi: 10.3390/SU142215347

Zhao Y Y, Liu Z F, Wu J G, 2020. Grassland ecosystem services: a systematic review of research advances and future directions. *Landscape Ecology*, 35(4): 793–814. doi: 10.1007/s10980-020-00980-3

Zhou W, Yang H, Huang L et al., 2017. Grassland degradation remote sensing monitoring and driving factors quantitative assessment in China from 1982 to 2010. *Ecological Indicators*, 83: 303–313. doi: 10.1016/j.ecolind.2017.08.019

Zuo Wanqing, Wang Yuhui, Wang Fengyu et al., 2009. Effects of enclosure on the community characteristics of *Leymus chinensis* in degenerated steppe. *Acta Prataculturae Sinica*, 18(3): 12–19. (in Chinese)