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BAI Yongfei
*State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China; Inner Mongolia Grassland Ecosystem Research Station, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China; College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China*

*See next page for additional authors*

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## Abstract

Grassland ecosystems of Northern China, the headwaters region and water resource conservation areas for the Yellow River, the Yangzi River, the Lancang River, and the Luanhe River, are important ecological security barriers in China. They play extremely important roles in maintaining multiple ecosystem functions and services and sustaining multinational cultural diversity. However, the grassland ecosystems of Northern China have experienced widespread deterioration in functions and services since the last several decades due to the overexploitation of production functions at the cost of their ecological functions. Therefore, assessment of ecosystem services and ecological regionalization of grasslands in Northern China are needed for optimizing their production functions and ecological functions, establishing ecological security barriers, and achieving ecological civilization. Based on the spatial patterns of key ecosystem services and environmental conditions, we propose seven ecoregions and twenty-five sub-ecoregions across grassland ecosystems in Northern China. The ecological regionalization of grasslands can be used to guide sustainable grassland management, restoration of degraded grasslands, and biodiversity conservation in Northern China.

## Keywords

grasslands of Northern China; ecosystem services; value of ecosystem services; ecological regionalization; optimizing production functions and ecological functions; ecological security barrier

## Authors

BAI Yongfei, ZHAO Yujin, WANG Yang, and ZHOU Kailing

## Corresponding Author(s)

BAI Yongfei [1,2,3*]

1 State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China

2 Inner Mongolia Grassland Ecosystem Research Station, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China

3 College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China

BAI Yongfei Principle Investigator and Ph.D. Supervisor of Institute of Botany, Chinese Academy of Sciences (CAS), Professor of the University of Chinese Academy of Sciences, and Director of the Inner Mongolia Grassland Ecosystem Research Station, CAS. He won the "Distinguished Young Scholar Program" of the National Natural Science Foundation of China (NSFC) in 2018. He serves as the President of the Plant Ecology Branch of the Chinese Society for Plant Sciences. His main research areas include: relationships between biodiversity and multiple ecosystem functions; sensitivity and responses of ecosystem services to global change drivers; and restoration of degraded grasslands and ecosystem management. He has published more than 150 papers in peer reviewed journals, such as *Nature*, *PNAS*, *Ecology Letters*, *Ecology*, *Journal of Applied Ecology*, and *Global Change Biology*. E-mail:yfbai@ibcas.ac.cn

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# Assessment of Ecosystem Services and Ecological Regionalization of Grasslands Support Establishment of Ecological Security Barriers in Northern China

BAI Yongfei[1,2,3], ZHAO Yujin[1,2], WANG Yang[1,2], ZHOU Kailing[1,3]

*1. State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China;*
*2. Inner Mongolia Grassland Ecosystem Research Station, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China;*
*3. College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China*

**Abstract:** Grassland ecosystems of Northern China, the headwaters region and water resource conservation areas for the Yellow River, the Yangzi River, the Lancang River, and the Luanhe River, are important ecological security barriers in China. They play extremely important roles in maintaining multiple ecosystem functions and services and sustaining multinational cultural diversity. However, the grassland ecosystems of Northern China have experienced widespread deterioration in functions and services since the last several decades due to the overexploitation of production functions at the cost of their ecological functions. Therefore, assessment of ecosystem services and ecological regionalization of grasslands in Northern China are needed for optimizing their production functions and ecological functions, establishing ecological security barriers, and achieving ecological civilization. Based on the spatial patterns of key ecosystem services and environmental conditions, we propose seven ecoregions and twenty-five sub-ecoregions across grassland ecosystems in Northern China. The ecological regionalization of grasslands can be used to guide sustainable grassland management, restoration of degraded grasslands, and biodiversity conservation in Northern China. **DOI:** 10.16418/j.issn.1000-3045.20200515003-en

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Grasslands are an important part of the terrestrial ecosystem. They not only provide meat, milk, skin, wool, and other products with direct economic value for human beings, but also have important ecological service functions such as climate regulation, water conservation, wind prevention and sand fixation, biodiversity conservation, primary productivity, and carbon sequestration [1,2]. According to statistics, grasslands take up 40.5% of the world's total land area (excluding Greenland and Antarctica) with an area of $5.25 \times 10^9$ $hm^2$, store 34% of the total carbon in terrestrial ecosystem, maintain 30% of net primary productivity (NPP), and provide about 30%–50% of global livestock products [1]. Mainly distributed in arid and semi-arid areas and accounting for 88% of the total area, grasslands feed up 25% of the world population.

Grasslands (nearly $4 \times 10^8$ $hm^2$) account for China's largest land resource, covering nearly 41.7% of the national land area [3]. Grasslands in Northern China cover an area of about $3 \times 10^8$ $hm^2$ [4] and are mainly distributed in 13 provinces and regions, including Xinjiang, Tibet, Qinghai, Gansu, Sichuan, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Hebei, Liaoning, Jilin, and Heilongjiang, covering 11 key pastoral areas in China. Grasslands in Northern China are mainly composed of the temperate steppes distributed continuously in Inner Mongolia Plateau, which constitute the eastern area of Eurasia Steppe. According to the range classification system of China, the natural grasslands in China can be divided into 18 categories, including temperate steppes, lowland meadows, mountain meadows, alpine steppes, alpine meadows and temperate deserts, which are widely distributed in Northern China, account for more than 85% of the total area of natural grasslands in China, and constitute the main body of natural grasslands in China (Fig. 1). They are important ecological security barriers in Northern China, as well as the headwaters regions and water conservation areas of the Yellow River, the Yangtze River, the Lancang River, and the Luanhe River [2,3]. Therefore, grasslands in Northern China play an important role in protecting ecological security and improving ecosystem services and stability in China [2].

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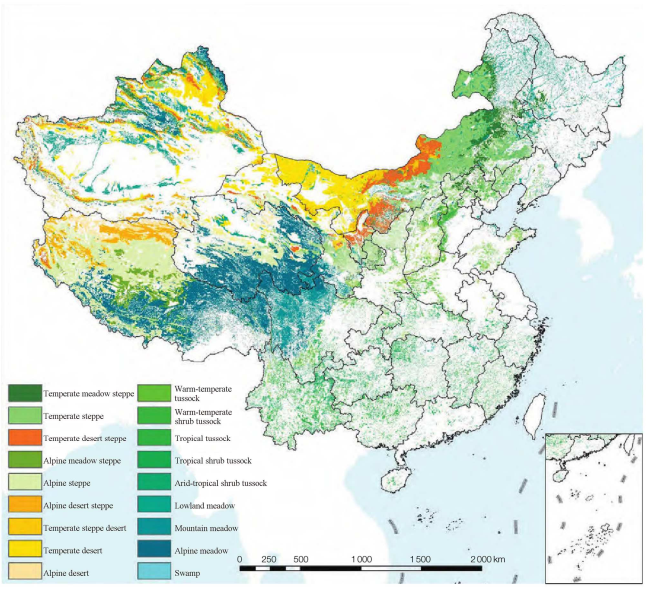


**Fig. 1** Types and distribution of grasslands in China.(Lack of data in Hong Kong, Macao, and Taiwan).

About 90% of the natural grasslands in China are in different degrees of degradation, of which more than 60% are seriously degraded. Long-term overgrazing, reclamation of farmland from grasslands, climate change, insufficient national investment, and the deviation of policy in pastoral areas are the main causes of grassland degradation in China [2,5,6]. For a long time, China has attached great importance to the production function of grasslands in animal husbandry production, while ignoring their ecological function, which leads to excessive utilization of their production function. The problems of overgrazing, excessive digging, and excessive farming of grasslands are very serious. From 1960s to 1980s, a large area of high-quality grasslands was reclaimed for agricultural use, which is the main reason for the degradation of grasslands and the deterioration in their ecological function and ecosystem service function. When it comes to the natural factors, climate warming, drought, insect and rodent pests also accelerate the degradation. At the same time, the deviation of policy as well as relatively backward management is also important factors leading to grassland degradation in China. For example, most policies and management models of pastoral areas in China are copied directly from those applied to agricultural areas, despite the different environmental conditions and production characteristics. Pastoral areas suffer from fragile environmental conditions, volatile climate, and many natural disasters. Water is the main factor limiting the primary productivity. Compared with agricultural products, the production process of animal products is more complex, involving both vegetation production and animal production. The production base of pastoral areas is weak with extensive management and large profits in circulation. It is necessary to coordinate the ecological function and production function in grassland management to realize the harmonious development of humans, grasslands and domestic animals. A large number of studies have shown that overgrazing reduces vegetation coverage, primary productivity, biodiversity, and soil nutrient and water-holding capacity; water loss and soil erosion have been intensified, enhancing the sensitivity to climate change. Thus, the ecosystem functions on different spatial and temporal scales are seriously affected, and the degradation succession of grasslands has been accelerated. As a result, the ecosystem services of grasslands are declining day by day, and the disasters such as insect and rodent pests and sandstorms occur frequently, which seriously threatens the ecological security of Northern China and its surrounding areas [5–7]. Since 2000, China has successively implemented the Beijing-Tianjin dust storm source control project, pastureland rehabilitation, and grassland ecological protection subsidy and reward policy, and the grassland ecology has been significantly improved. However, the passive situation that the grasslands in Northern China are improved locally but degrade on the whole and that the speed of governance cannot catch up with that of degradation needs to be fundamentally reversed, the prominent contradiction between “humans, mines, grasslands, and domestic animals” in pastoral areas needs to be solved, and the concept of grass-based animal husbandry production needs to be innovated and developed.

We have to clarify the current situation and spatial pattern of grassland ecosystem services in Northern China, carry out ecosystem service assessment, and formulate the main ecological regionalization of grasslands in Northern China, so that we can construct and optimize the ecological security barrier system, scientifically allocate the ecological functions and production functions of grasslands, promote ecological civilization, coordinate the integrated protection and restoration of mountains, rivers, forests, fields, lakes, and grasses, and build Beautiful Grasslands and a Beautiful China, thus achieving the national major scientific and technological needs of harmonious coexistence of human and nature. The results of ecosystem service assessment and main ecological regionalization in Northern China will provide important scientific and technological support for territorial spatial planning, scientific layout of important ecosystem protection and restoration projects, and overall promotion of ecological protection and restoration work.

## 1 Ecosystem services and value assessment

### 1.1 Ecosystem services

Ecosystem services refer to the environmental conditions and processes provided by the ecosystem to maintain and realize human survival and development. It is the benefit obtained by human beings from the ecosystem and the basis for human survival and development [8,9]. Ecosystem services include support services, supply services, regulating services, and cultural services [9]. The ecological function refers to the size of components (including the material pool) of an ecosystem and the rate of its processes (such as material cycle and energy flow), including primary productivity, carbon sequestration, water conservation, wind prevention and sand fixation, biodiversity maintenance, etc., and its core connotation is ecosystem support services and regulating services. The production function means that the ecosystem provides humans with a variety of consumer products and resources (supply services), including livestock products, forage products, and edible and medicinal plants [2].

In order to accurately evaluate the carbon storage and its changes of grassland ecosystems in China, a leading strategic project of the Chinese Academy of Sciences about "the status, rate, mechanism, and potential of carbon sequestration in ecosystem" (hereinafter referred to as "carbon project") put forward a research subject on "carbon sequestration status, change, and mechanism of grassland ecosystem in China" (2011–2015) (hereinafter referred to as "grassland research subject"). A total of 4 207 sample plots were set up in different grassland types across the country. On the basis of unified investigating, sampling and testing methods, the carbon sequestration status and potential of vegetation and soil, and grassland primary productivity in China were estimated through data integration analysis combined with remote sensing and modeling [10]. In this paper, the results of the "grassland research subject" were directly used for the primary productivity, vegetation and soil carbon storage, and carbon sequestration rate of grasslands in China. Meanwhile, the water conservation, wind prevention and sand fixation and, biodiversity maintenance services of grassland ecosystems were also estimated with reference to the results of other related studies.

(1) Primary productivity. The aboveground biomass of natural grassland vegetation in China is 543 million tons, and the underground biomass is 4.836 billion tons. The aboveground biomass and underground biomass in Inner Mongolia, Xinjiang, Qinghai, Tibet, Sichuan, Gansu, Heilongjiang, Jilin, Liaoning, Hebei, Shanxi and Shaanxi account for 68.13% and 83.8% of the total biomass in China, respectively. According to the measured data of vegetation productivity, the NPP of grassland vegetation in China is estimated to be $1.474 \times 10^9$ $t \cdot a^{-1}$, with an average of 4.99 $t \cdot hm^{-2} \cdot a^{-1}$. However, there is a great difference in NPP between different grassland types.

(2) Carbon sequestration. The total carbon storage of grasslands in China is 28.95 PgC, including 1.82 PgC of vegetation carbon storage and 27.13 PgC of soil organic carbon storage. From the spatial distribution, the carbon density and carbon storage of grasslands in China decrease gradually from northwest to southeast (Fig. 2). Grasslands in Inner Mongolia, Xinjiang, Qinghai, and Tibet have the widest distribution and the highest carbon storage (6.80 PgC, 6.13 PgC, 5.68 PgC, and 5.40 PgC, respectively), accounting for 60% of the total amount in China. The carbon storage in Sichuan, Heilongjiang, Yunnan, and Gansu is 2.97 PgC, 2.28 PgC, 1.70 PgC, and 1.46 PgC, respectively, accounting for 21%. Other 23 provinces and regions only account for 19% due to the small grassland distribution or relatively low total carbon density. Different from forests, most of the vegetation carbon of grasslands is stored in the underground root system, accounting for 92% of total carbon storage of grasslands. As the most important component of the carbon storage in grassland ecosystems, the carbon density of the soil carbon pool is 19 times that of vegetation. The average carbon sequestration rate of grassland vegetation in China is 250 $tC \cdot hm^{-2} \cdot a^{-1}$, and the annual carbon sequestration is 1 215 TgC. This is basically consistent with the results of remote sensing model inversion that the annual carbon sequestration of grassland vegetation in China is 1 160 TgC based on the normalized difference vegetation index (NDVI) and CASA model inversion. In terms of grassland types, alpine steppe is 734 TgC in annual carbon sequestration; temperate steppe is 182 TgC; warm-temperate and tropical tussock/shrub tussock is 56 TgC; intrazonal meadow is 233 TgC. The provinces and regions with a large area of grasslands also enjoy high annual net carbon sequestration. For example, the annual carbon sequestration of Tibet, Qinghai, Sichuan, Inner Mongolia, and Xinjiang account for 34%, 20%, 12%, 9%, and 9% in China.

(3) Water conservation. On the basis of land cover, precipitation, NDVI, and the rainfall storage capacity, the average water conservation of grasslands in China from 1980 to 2000 was $1.161\,7 \times 10^{11}$ $m^3 \cdot a^{-1}$, and that in Northern China was $3.747 \times 10^{10}$ $m^3 \cdot a^{-1}$. From 2000 to 2010, the average annual water conservation of grasslands in China was $1.183\,8 \times 10^{11}$ $m^3 \cdot a^{-1}$, and that in Northern China was $4.093 \times 10^{10}$ $m^3 \cdot a^{-1}$ [11]. Grasslands in Northern China were characterized by great spatial heterogeneity of water conservation services, which were concentrated in the central and eastern regions of the Qinghai-Tibet Plateau and the Inner Mongolia Plateau. From 1990 to 2010, the average water conservation of grasslands in Tibet was $2.749 \times 10^{10}$ $m^3 \cdot a^{-1}$ [12,13], and that of the grasslands (9 786 $km^2$) in Xilin River Basin, Inner Mongolia was $4 \times 10^7$ $m^3 \cdot a^{-1}$ [14].

(4) Wind prevention and sand fixation. Wind prevention and sand fixation is an important ecosystem service provided by arid and semi-arid grasslands. Its material quality can be estimated by revised wind erosion equation (RWEQ), revised universal soil loss equation (RUSLE), and other wind erosion models. Relevant studies have estimated the benefits of wind prevention and sand fixation in some grassland areas in Northern China. For instance, Sun et al. [15] estimated that the benefit of wind prevention and sand fixation of grasslands in Qinghai-Tibet Plateau from 1984 to 2013 was $2.72 \times 10^7$ $t \cdot a^{-1}$ by the RUSLE; Sun et al. [16] estimated that the benefit of wind prevention and sand fixation of grasslands in the Loess Plateau from 1990 to 2010 was $7.7 \times 10^9$ $t \cdot a^{-1}$; Wang et al. [17] estimated that the benefit of wind prevention and sand fixation of grasslands in Ningxia from 2000 to 2015 was $7.298 \times 10^6$–$4.120 \times 10^7$ $t \cdot a^{-1}$ by the RWEQ; Jiang et al. [18] estimated that in Inner Mongolia was $5.758 \times 10^9$ $t \cdot a^{-1}$.

(5) Biodiversity maintenance. According to incomplete

statistics, there are 254 families, more than 4 000 genera and 9 700 species of grassland plants in China, including 316 toxic species of 138 genera in 52 families [19,20]. In addition, there are more than 2 000 species of wild animals in China's grassland areas, including 14 of Class I protected animals and 30 of Class II protected animals. Rich biodiversity resources constitute the gene pool of wild animal and plant resources in China, especially the most important ones of drought-enduring, hardy, salt-tolerant and medicinal plants. At present, under the influence of long-term overgrazing, reclamation, climate change, environmental pollution, biological invasion, and other factors, grassland biodiversity in China has significantly decreased, leading to the decline of the ecological function and ecosystem stability of grasslands [21–23].

## 1.2 Value assessment of ecosystem services

Value assessment of ecosystem services serves as an important evidence and basis for making decisions about regional ecological environment protection, ecological economic accounting, and ecological compensation, implementing ecological regionalization, and protecting and restoring natural ecosystems [24]. Since 1997, when Costanza et al. [25] first valued the services of major ecosystem types in the world, a lot of relevant studies of the service value of grassland ecosystems have been carried out by the researchers in China and abroad [26]. The credibility of China's national grassland ecological value accounting is high, ranging from 0.87 trillion to 7.5 trillion yuan [26].

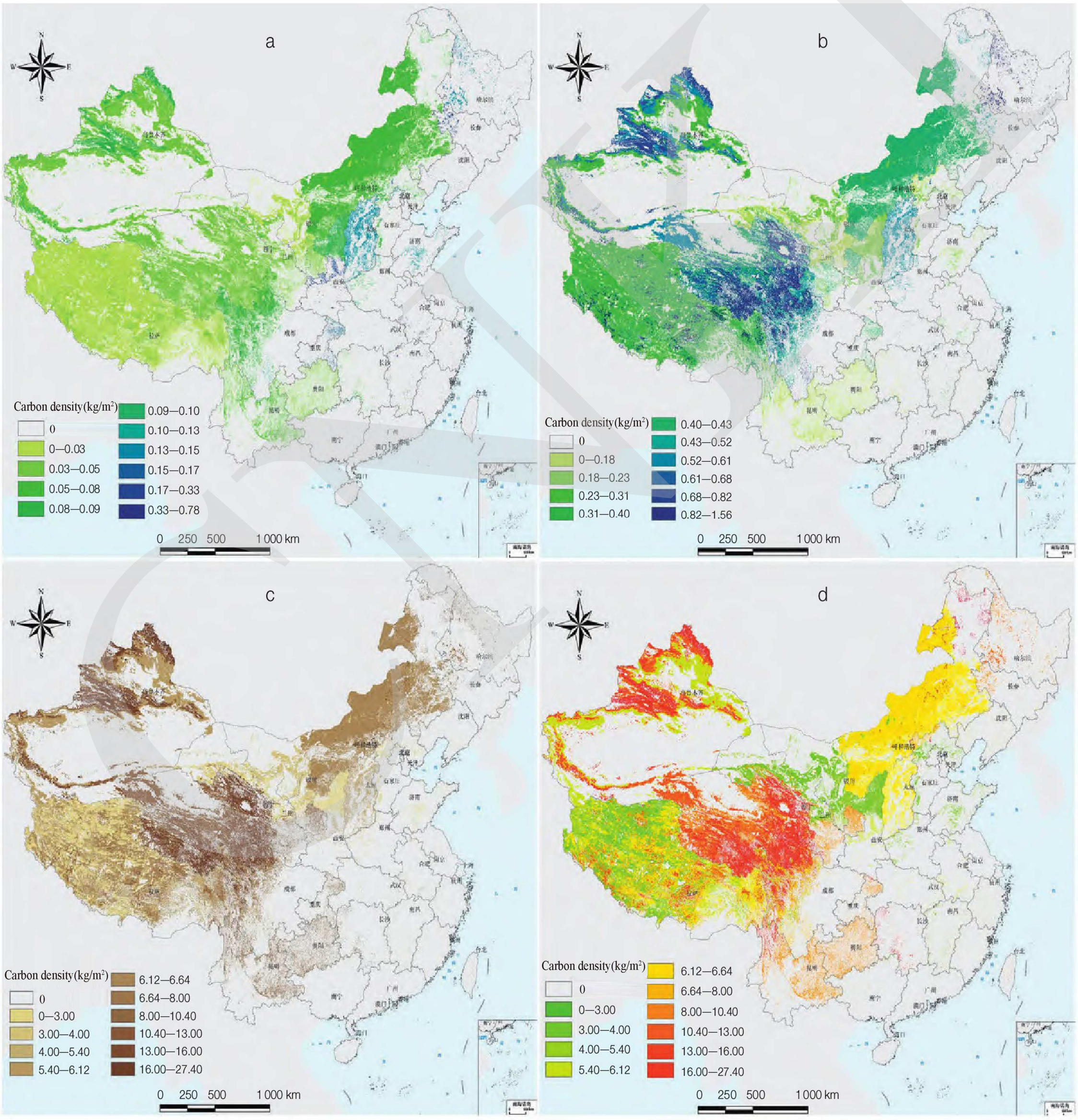


**Fig. 2** Distribution of total carbon density above the ground (a), below the ground (b), in soil (c), and in ecosystems (d) of grassland vegetation in China

 

According to the relevant references [27–30], the average value of grassland ecological services per unit area in China is 1 920.5–4 475.8 yuan/hm$^{-2}$. Since the grassland area in Northern China is about $3 \times 10^8$ hm$^2$, its ecological service value is 576.45 to 1 345.20 billion yuan. The value of ecosystem services varies greatly by region and grassland type. Swamps possess the highest ecosystem service value, followed by warm-temperate shrub tussocks, warm-temperate tussocks, lowland meadows, temperate meadow steppes, temperate steppes, alpine meadows, and alpine steppes, while alpine deserts have the lowest value. From the regional perspective, the service value per unit area of grasslands in the east of Inner Mongolia such as Hulunbeir, Horqin, and Xilingol, the northwest of Xinjiang and the east and northeast of Qinghai-Tibet Plateau are higher than that in central and western Inner Mongolia and western Qinghai-Tibet Plateau.

## 2 Principles and methods of ecological regionalization

Ecological regionalization is the geological area distribution based on the spatial differentiation of regional ecosystem types, eco-environmental sensitivity, the threat process and effect of ecosystem, and ecosystem structure, process and service. In 1976, American ecologist Bailey put forward and worked out the plan of American ecological regionalization from the perspective of ecosystem for the first time. Since then, ecologists along with international organizations have refined and improved the principles, index systems and methods of ecological regionalization [24,31]. China's ecological regionalization started late, with the Chinese ecological regionalization launched by Fu et al. [31] as a representative. In 2008, the Ministry of Environmental Protection and the Chinese Academy of Sciences jointly issued the *National Ecological Regionalization*, which divided the whole country into 31 grade I ecoregions in three categories, 67 grade II ecoregions in nine categories, and 208 grade III ecoregions. It defines the important areas to ensure national ecological security, and provides scientific guidance for the rational management and sustainable use of natural resources, the coordination between economic society and ecological protection, and their healthy development. In 2012, Xie et al. [24] divided China into 33 water conservation ecoregions, 57 soil and water conservation ecoregions, 19 wind prevention and sand fixation ecoregions, 11 coastal protection ecoregions, 62 product supply ecoregions, and 86 biodiversity conservation ecoregions based on the existing three-level ecological regionalization scheme with the county as the smallest division unit. Jia et al. [3] proposed the first grassland resource regionalization in China after the first general grassland investigation in the 1980s and 1990s based on the spatial differentiation of grassland resources and the ecological factors such as topography, soil, and vegetation. It divided grasslands into seven ecoregions, 29 sub-ecoregions, and 74 sub-districts. However, this natural division did not take the impacts of human activities and climate change on the structure, function and services of grassland ecosystems into consideration.

At present, in the face of the requirements of important national strategies such as ecological civilization, Beautiful China Initiative, and the integrated protection and restoration of mountains-rivers-forests-farmlands-lakes-grasslands, it is urgent to construct the main ecoregions of grasslands in China, especially in the north. Considering the ecological service and ecological carrying capacity of grasslands, we should scientifically guide and reasonably allocate the ecological and productive functions of grasslands, which will offer important scientific and technological support for the formulation of regional territorial spatial planning, scientific layout of important grassland ecosystem protection and restoration projects in Northern China, and overall promotion of ecological protection and restoration.

(1) Principles of grassland ecological regionalization in Northern China. ① Regional differentiation of ecological elements. It takes the regional differentiation of climate, topography, soil, vegetation and other natural elements as the basis. ② Leading principle. On the basis of the regional differentiation of grassland types, this principle requires that the differences of climate, topography and other factors should be subject to the differentiation of main grassland types; the ecosystem services of different grassland types should be taken into account; the non-dominant function should be subordinate to the dominant function. ③ Combination of ecological priority with green development. We should adhere to the eco-priority and place-based principle, in terms of balancing the grassland production and social economic condition, grazing intensity, layout and development of animal husbandry, grassland management, cultivating technology, nature reserves and national parks, and rationally allocating ecological and production functions. ④ Grade-based regionalization. We should preserve the integrity of the administrative boundaries, especially those of counties.

(2) Ecological regionalization of grasslands in Northern China. On the basis of grassland type, grassland resource regionalization and ecological service regionalization in China, we are supposed to consider the important ecological parameters such as climate humidity, topography, soil, and vegetation coverage, and take into account the ecosystem services (including primary productivity, carbon sequestration, water conservation, wind prevention and sand fixation, biodiversity maintenance, etc.), and ecological sensitivity assessment of land desertification and salinization, while keeping the integrity of the county boundary and setting the regionalization scheme and the boundaries between the districts (Fig. 3).

 

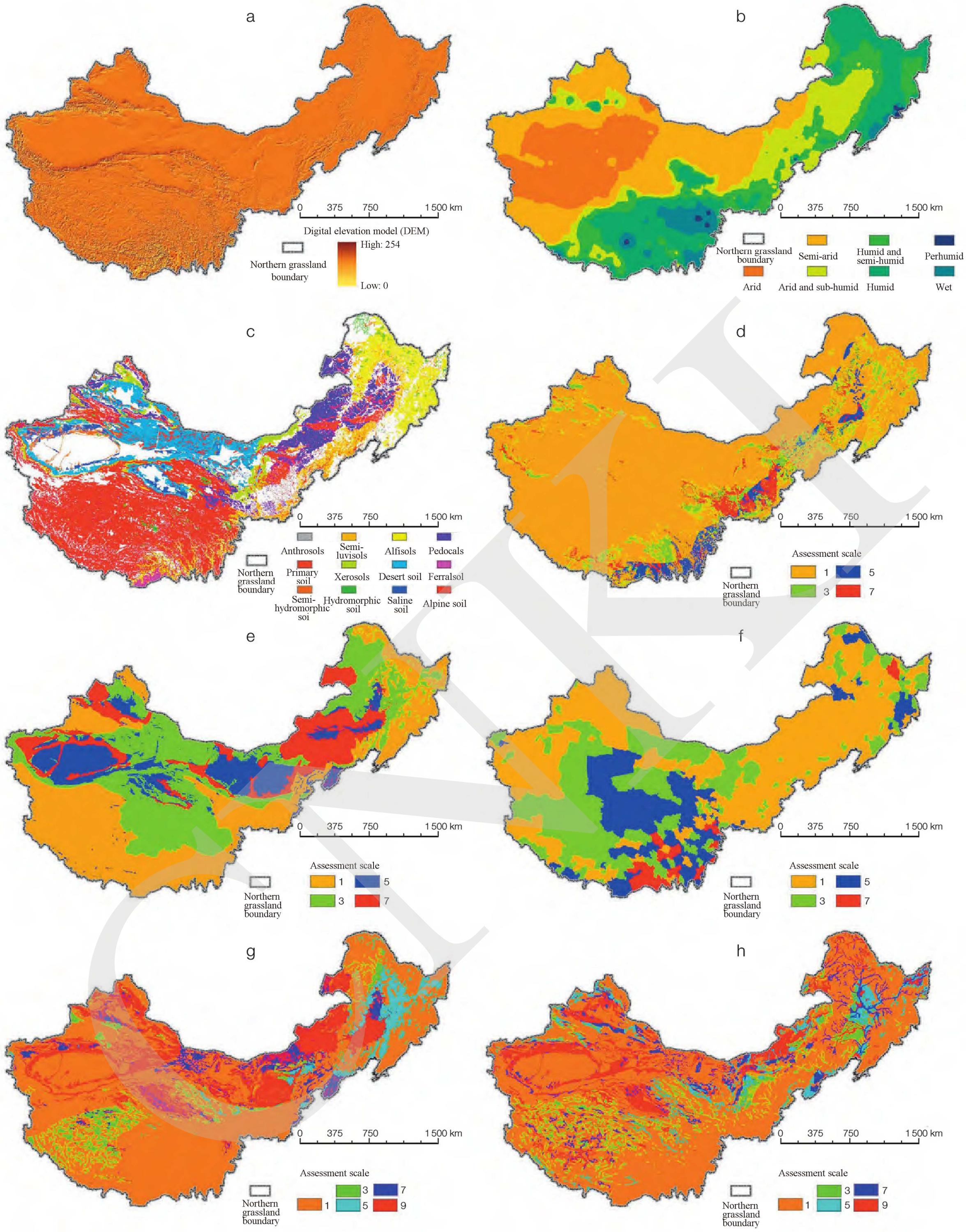


**Fig. 3** Grassland topography in Northern China (a), climate (climate-humidity index, b), soil (soil type, c; levels of soil conservation significance, d), ecological parameters (significance evaluation of wind prevention and sand fixation, e; assessment of biodiversity maintenance and conservation, f), and sensitivity assessment (sensitivity of desertification, g; assessment of salinization sensitivity, h)

The humidity index is derived from China meteorological background dataset (http://www.resdc.cn/DOI); the soil types are derived from *Geomorphologic Atlas of the People's Republic of China* (1:1 000 000); the ecosystem services and sensitivity assessment is derived from China ecosystem assessment and ecological security database (http://www.ecosystem.csdb.cn/ecoass/ecoplanning.jsp).

 

## 3 Overview and implementation measures of ecological regionalization

### 3.1 Overview

According to the above principles and methods, grasslands in Northern China were divided into seven ecoregions and 25 sub-ecoregions (Fig. 4), which are all named after place + grassland type or subgroup. See Table 1 for the names, main ecological functions, climatic conditions, main problems and ecological sensitivity of each area.

### 3.2 Implementation measures for ecoregions of grasslands in Northern China

In the face of the national major needs of coordinating the integrated protection and restoration of mountains-rivers-forests-farmlands-lakes-grasslands, ecological civilization, and Beautiful China Initiative, we take into account the main problems faced by the ecoregions and their ecological and environmental sensitivity based on the above regionalization plan. The principle of ecological priority should be adhered and the spatial differentiation of ecosystem services and ecological carrying capacity is considered. Consequently, the key measures taken in the ecoregions are proposed with the reasonable allocation of ecological production functions of grasslands as the starting point.

(1) Humid and semi-humid meadow steppe and meadow ecoregion. Water conservation, carbon sequestration, soil and biodiversity conservation are the cores of ecosystem services and ecological functions in this ecoregion. This ecoregion adheres to the principle of ecological priority and organic combination of production and ecology, strictly implementing the measure that livestock fits grass, and fundamentally curbing overgrazing and grassland degradation. To speed up the restoration of degraded grasslands, the management measures such as grazing prohibition, rest grazing, reducing grazing, and rotational grazing are adopted. The development of mineral resources is strictly restricted to protect the black soil and prohibit the reclamation of grasslands. To speed up the restoration and reconstruction of seriously degraded grasslands, measures such as resowing grass seed on native soil, soil bioremediation, fertilization, loosening soil and cutting roots are adopted. At the same time, we should innovate the development mode of grass-based animal husbandry, develop high-efficiency artificial grasslands, high-quality grass product processing, and grassland typical creatures cultivation and breeding technology, and explore a new mode of high-quality development of grass-based animal husbandry.

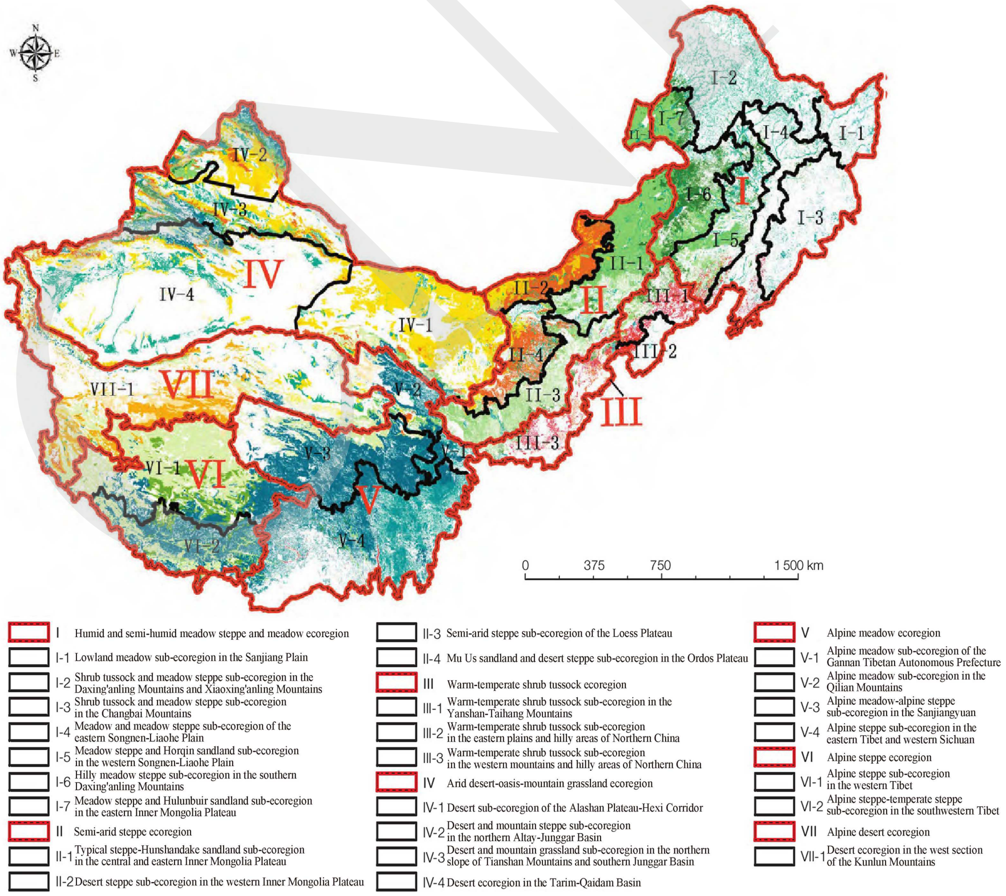


**Fig. 4** Ecological regionalization of grasslands in Northern China

**Table 1** General situation, main functions and ecological sensitivity of grassland ecological regionalization in Northern China

| Grade I ecoregion | Code of sub-ecoregion | Name of sub-ecoregion | Area of sub-ecoregion (hm²) | Main functions | Number of national nature reserves (proportion of land area in the sub-ecoregion) | Climate condition | | | Key issues and ecological sensitivity |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Mean annual precipitation (mm) | Mean annual temperature (°C) | Drought index | |
| Humid and semi-humid meadow steppe and meadow ecoregion | I-1 | Lowland meadow sub-ecoregion in the Sanjiang Plain | $1.0\times10^7$ | Water conservation, carbon sequestration, and hydrological regulation | 14（17.8%） | 558.5 | 2.9 | 0.9 | Wetland and swamp area is decreasing, and water conservation and carbon sequestration as well as hydrologic regulation is declining; sensitive to climate change and wetland reclamation |
| | I-2 | Shrub tussock and meadow steppe sub-ecoregion in the Daxing'anling Mountains and Xiaoxing'anling Mountains | $3.3\times10^7$ | Water, soil, and biodiversity conservation | 29（6.5%） | 504.2 | 2.4 | 0.8 | Biodiversity is reduced, and the original ecosystem is threatened; sensitive to soil and water loss and biodiversity |
| | I-3 | Shrub tussock and meadow steppe sub-ecoregion in the Changbai Mountains | $2.2\times10^7$ | Water, soil, and biodiversity conservation | 25（5.2%） | 699.0 | 3.2 | 0.8 | Soil and water loss, water environment pollution, vegetation degradation, and landscape fragmentation are severe, and land productivity is low; sensitive to biodiversity, soil and water loss, and meteorological disaster |
| | I-4 | Meadow and meadow steppe sub-ecoregion of the eastern Songnen-Liaohe Plain | $2.0\times10^7$ | Soil and water conservation | 17（1.5%） | 603.0 | 5.1 | 0.9 | Steppe degradation, soil desertification and salinization are serious, and land productivity is low; sensitive to soil erosion and desertification; |
| | I-5 | Meadow steppe and Horqin sandland sub-ecoregion in the western Songnen-Liaohe Plain | $1.9\times10^7$ | Wind prevention and sand fixation, soil conservation | 19（4.2%） | 440.6 | 5.5 | 1.3 | Desertification, salinization, and degradation of grassland are serious; sensitive to meteorological disasters along with quicksand erosion and salinization |
| | I-6 | Hilly meadow steppe sub-ecoregion in the southern Daxing'anling Mountains | $1.6\times10^7$ | Soil and biodiversity conservation | 8（6.3%） | 414.2 | 2.2 | 1.2 | Steppe degradation and desertification are serious; sensitive to biodiversity and soil erosion |
| | I-7 | Meadow steppe and Hulunbuir sandland sub-ecoregion in the eastern Inner Mongolia Plateau | $0.6\times10^7$ | Wind prevention and sand fixation, soil and biodiversity conservation | 2（9.6%） | 360.2 | 3.3 | 1.2 | Steppe degradation and desertification, soil erosion, and blown sand disaster are serious; sensitive to biodiversity |
| Semi-arid steppe ecoregion | II-1 | Typical steppe-Hunshandake sandland sub-ecoregion in the central and eastern Inner Mongolia Plateau | $2.5\times10^7$ | Wind prevention and sand fixation, soil and biodiversity conservation | 5（7.7%） | 307.0 | 1.8 | 1.4 | Steppe degradation and desertification are serious; extremely sensitive to land degradation and biodiversity |
| | II-2 | Desert steppe sub-ecoregion in the western Inner Mongolia Plateau | $1.1\times10^7$ | Wind prevention and sand fixation, and soil conservation | 1（1.4%） | 182.5 | 4.5 | 3.0 | As the source of sandstorm in China, this sub-ecoregion suffers from serious soil erosion and quicksand; sensitive to biodiversity |
| | II-3 | Semi-arid steppe sub-ecoregion of the Loess Plateau | $2.0\times10^7$ | Erosion control, wind prevention and sand fixation | 8（1.5%） | 417.6 | 6.4 | 1.4 | Land desertification, wind and water erosion are serious; sensitive to soil and water loss, salinization and denudation |
| | II-4 | Mu Us sandland and desert steppe sub-ecoregion in the Ordos Plateau | $1.3\times10^7$ | Biodiversity conservation, wind prevention and sand fixation, and soil conservation | 5（7.5%） | 238.7 | 6.0 | 2.8 | Grassland degradation, desertification, and soil and water loss are serious; highly sensitive to biodiversity and soil erosion |
| Warm-temperate shrub tussock ecoregion | III-1 | Warm-temperate shrub tussock sub-ecoregion in the Yanshan-Taihang Mountains | $1.0\times10^7$ | Water and soil conservation | 8（2.1%） | 502.7 | 6.0 | 1.2 | Soil and water loss is serious and the ecological carrying capacity is low; sensitive to soil erosion |
| | III-2 | Warm-temperate shrub tussock sub-ecoregion in the eastern plains and hilly areas of Northern China | $0.5\times10^7$ | Biodiversity and water conservation | 3（0.6%） | 530.7 | 11.7 | 1.4 | Water shortage and salinization are serious; highly sensitive to water stress and sensitive to the desertification of northwest regions, with geological disasters occurring frequently |
| | III-3 | Warm-temperate shrub tussock sub-ecoregion in the western mountains and hilly areas of Northern China | $1.6\times10^7$ | Soil conservation | 15（1.6%） | 547.8 | 8.4 | 1.2 | Vegetation coverage is low and the soil and water loss is serious; sensitive to soil erosion |

Table 1 continued

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Arid desert-oasis-mountain grassland ecoregion | Ⅳ-1 | Desert sub-ecoregion of the Alashan Plateau-Hexi Corridor | 4.9×10$^7$ | Wind prevention and sand fixation, biodiversity conservation | 14（12.2%） | 105.2 | 5.5 | 8.7 | Grassland degradation and desertification are serious, and sand dunes are activated, threatening oasis security and biodiversity conservation; highly sensitive to land degradation |
| | Ⅳ-2 | Desert and mountain steppe sub-ecoregion in the northern Altay-Junggar Basin | 2.0×10$^7$ | Wind prevention and sand fixation, soil and biodiversity conservation | 5（2.0%） | 177.0 | 2.5 | 5.2 | Grassland degradation and desertification are serious, and insect and rodent pests appear frequently; highly sensitive to biodiversity and habitat |
| | Ⅳ-3 | Desert and upland meadow sub-ecoregion in the northern slope of Tianshan Mountains and southern Junggar Basin | 2.9×10$^7$ | Biodiversity and soil conservation | 5（2.2%） | 225.3 | 3.6 | 5.4 | Grassland degradation, desertification, soil and water loss, and regional salinization are serious; highly sensitive to biodiversity and habitat in the west, and land degradation and soil erosion in the east |
| | Ⅳ-4 | Desert-oasis sub-ecoregion in the Tarim-Qaidam Basin | 16.0×10$^7$ | Wind prevention and sand fixation, biodiversity conservation | 3（6.5%） | 66.1 | 8.5 | 11.2 | Grassland degradation, desertification, insect and rodent pests are serious, and soil salinization is increasing, endangering oasis and biodiversity; highly sensitive to land desertification, and extremely sensitive to salinization, biodiversity, and habitat |
| Alpine meadow ecoregion | Ⅴ-1 | Alpine meadow sub-ecoregion of the Gannan Tibetan Autonomous Prefecture | 0.4×10$^7$ | Water and biodiversity conservation | 1（21.0%） | 589.7 | 0.7 | 1.1 | Overgrazing, overstocking, and grassland degradation are serious; sensitive to soil erosion and biodiversity |
| | Ⅴ-2 | Alpine steppe sub-ecoregion in the Qilian Mountains | 1.3×10$^7$ | Biodiversity conservation, wind prevention and sand fixation | 4（7.5%） | 336.4 | 2.9 | 1.9 | Grassland degradation and desertification are serious, and water conservation capacity is decreasing; highly sensitive to biodiversity and habitat, and moderately sensitive land desertification and soil erosion |
| | Ⅴ-3 | Alpine meadow-alpine steppe sub-ecoregion in the Sanjiangyuan | 3.7×10$^7$ | Biodiversity and water conservation | 1 national park（100%） | 391.7 | 5.1 | 1.0 | Grassland degradation, mobile sand dune, blown sand disaster, and desertification are serious, and biodiversity and water conservation capacity are reducd |
| | Ⅴ-4 | Alpine meadow sub-ecoregion in the eastern Tibet and western Sichuan | 5.6×10$^7$ | Water and soil conservation | 29（7.6%） | 625.9 | 2.0 | 1.1 | Grassland degradation, desertification, soil and water loss, and mountain disasters are serious; highly sensitive to soil erosion and wildlife habitat, moderately sensitive to desertification, and sensitive to biodiversity |
| Alpine steppe ecoregion | Ⅵ-1 | Alpine steppe-temperate steppe sub-ecoregion in the southwestern Tibet | 4.9×10$^7$ | Biodiversity and soil conservation | 5（39.6%） | 228.1 | 4.5 | 1.5 | Grassland degradation is serious; highly sensitive to desertification and salinization |
| | Ⅵ-2 | Alpine steppe ecoregion in the western Tibet | 2.4×10$^7$ | Biodiversity, soil, and water conservation | 3（18.8%） | 335.5 | 0.9 | 1.6 | Grassland degradation is serious; highly sensitive to soil and water loss and desertification |
| Alpine desert ecoregion | Ⅶ-1 | Desert ecoregion in the west section of the Kunlun Mountains | 9.1×10$^7$ | Biodiversity conservation | 1（27.4%） | 81.9 | 4.6 | 10.8 | Highly sensitive to wildlife habitat |

(2) Semi-arid steppe ecoregion. Wind prevention and sand fixation and soil conservation are the cores of ecosystem services and ecological functions in this ecoregion. In terms of implementation measures, we should strictly control the stock capacity of livestock under the principle of ecological priority and appropriate utilization, curb overgrazing and grassland degradation, and return some of the ecological space and carrying capacity to wild animals. It is necessary to accelerate the restoration of grasslands suffering from desertification, wind and water erosion, soil and water loss and salinization, and improve ecosystem services and its stability by taking measures including resowing grass seed on native soil and soil bioremediation. To solve the contradiction between grass and livestock and accelerate the restoration of degraded grassland, management measures such as grazing prohibition, rest grazing, reducing grazing, and rotational grazing should be adopted. The exploitation of mineral resources should be strictly restricted and the reclamation of grassland should be prohibited. We should also innovate the development mode of grass-based animal husbandry, moderately developing eco-tourism, and exploring a new pattern of grassland ecological protection and high-quality development of grass-based animal husbandry.

(3) Warm-temperate shrub tussock ecoregion. Water and soil conservation is the core of ecosystem services and ecological functions in this ecoregion. As for implementation

 

measures, we should adhere to the principle of giving priority to protection and limiting utilization, and turn sloping farmland to grassland and forest. According to the inherent mechanism and law of the ecosystem, the proportion of grass-shrub-arbor, plant-water relations, and the structure of artificial plant community in vegetation restoration should be scientifically arranged to accelerate vegetation restoration, effectively control soil erosion, and improve biodiversity and ecosystem stability. Meanwhile, during the vegetation restoration, natural restoration should be the main method to accelerate the restoration of degraded grasslands together with some other engineering measures. The development of mineral resources should be strictly restricted. Eco-tourism can be promoted appropriately in light of local conditions.

(4) Arid desert-oasis-mountain grassland ecoregion. Wind prevention and sand fixation, and soil, water, and biodiversity conservation are the cores of the ecosystem services and ecological functions in this ecoregion. The survival and development of human beings in arid areas depend on the oasis system. Therefore, when it comes to the implementation measures, we should give priority to ecology, determine the use pattern and intensity according to water resources and ecological carrying capacity, reasonably allocate water resources in the basin, control the scale of artificial oases, develop water-saving agriculture, and improve the use efficiency of water resources. Moreover, we should strictly restrict grazing and other production activities to protect desert vegetation. More efforts should be made to rehabilitate grasslands suffering from serious desertification, wind and water erosion, soil and water loss and salinization. We should also establish and improve the nature reserve system with national parks as the main body, convert most of the desert areas into nature reserves, and develop controllable desert and oasis tourism. We must explore a new pattern of ecological protection and sand industry development of fragile desert steppe.

(5) Alpine meadow ecoregion. Water, soil, and biodiversity conservation is the core of the ecosystem services and ecological functions in this ecoregion. We should adhere to the principle of giving priority to ecology and combining production and ecology in an organized manner, strictly implement the measure that livestock fits grass to control the livestock carrying capacity and fundamentally curb overgrazing, return some of the ecological space and carrying capacity to wild animals, establish and improve the natural reserve system with national parks as the main body, and develop the characteristic eco-tourism industry appropriately. To speed up the restoration of degraded grassland, the management measures such as grazing prohibition, rest grazing, reducing grazing, and rotational grazing must be adopted. To accelerate the restoration and reconstruction of seriously degraded grassland, the measures of resowing grass seed on native soil and soil bioremediation should be adopted. We also need to explore a new mode of high quality development of grass-based animal husbandry.

(6) Alpine steppe ecoregion. Biodiversity and water conservation is the core of the ecosystem services and ecological functions in this ecoregion. Under the principle of giving priority to ecology, we should control the intensity of human activities and livestock carrying capacity, and return no less than 50% of ecological space and carrying capacity to wild animals. We should establish and improve the nature reserve system with national parks as the main body, and strictly restrict the characteristic eco-tourism of fragile alpine grasslands. To speed up the restoration of degraded grassland, some management measures should be taken, such as grazing prohibition, rest grazing, reducing grazing, and rotational grazing, and excessive deforestation of wild plants should be eliminated.

(7) Alpine desert ecoregion. The core of the ecosystem services and ecological functions in this ecoregion lies in biodiversity conservation. In terms of implementation measures, we should limit the intervention of human activities in the natural ecosystem, strictly protect wildlife resources, establish a nature reserve system with national parks as the main body, and return most of the ecological space to wild animals.

## 4 Supporting measures for ecological regionalization of grasslands in Northern China

The implementation of ecological regionalization of grasslands in Northern China is of great significance for adhering to the principle of giving priority to ecology, scientifically allocating ecological and production functions of grasslands, coordinating the integrated protection and restoration of mountains-rivers-forests-farmlands-lakes-grasslands, constructing ecological security barrier system in Northern China, promoting the construction of ecological civilization and Beautiful China, and realizing green and high-quality development. Therefore, we put forward eight supporting measures for the implementation of grassland ecological regionalization in Northern China.

(1) The red line of ecological protection should be delimited and the ecological security space of land should be planned scientifically. Based on the main functions and ecological sensitivity of each ecoregion, it is necessary to determine the ecological protection red line, promote and optimize the construction of the nature reserve system with national parks as the main body, steadily promote the pilot work of national park system, improve the spatial layout of national nature reserves, and scientifically allocate the ecological functions of grasslands to implement ecological regionalization of grasslands in Northern China, optimize the land spatial pattern, and strengthen the ecological security barrier system in Northern China. At the same time, we should strengthen the connection between the grassland ecological regionalization in Northern China and the *Plan of Major Projects for the Protection and Restoration of*

 

*Important Ecosystems in China* (2021–2035) (hereinafter referred to as the *Plan*), and scientifically arrange the major projects for the protection and restoration of important ecosystems in Northern China based on the laws of natural ecosystem succession and the inherent mechanism. At present, the research on grassland production function in China is good, while the research on ecological function is weak. We should rely on the network of ecological system field scientific observation and research stations, strengthen the research on the succession law and internal mechanism of important grassland ecosystem, as well as the research and development of ecological restoration technology system and experimental demonstration mode, so as to provide scientific and technological support for the implementation of the *Plan*.

(2) The proportion of ecological and production water should be coordinated, and the development model of animal husbandry should be innovated. Water is the key driving factor of grassland ecosystem services in Northern China. Therefore, coordinating and optimizing the proportion of ecological, production and living water based on the carrying capacity of water resources and their spatial differentiation and dynamic changes is an important measure to maintain and improve grassland ecosystem services (including primary productivity, carbon sequestration, water and biodiversity conservation, wind prevention and sand fixation, soil conservation, etc.), as well as the key foundation for scientifically allocating their ecological and production functions. In the humid and semi-humid steppe ecoregion, the farming-pastoral ecotone, and some oasis areas, in light of the carrying capacity of water resources, it is an effective way to speed up the restoration of degraded grasslands by developing artificial grasslands and vegetative agriculture on part of cultivated land for rotation and fallow at a moderate scale with high efficiency, so as to improve the productivity of forage and feed, reduce the excessive dependence of animal husbandry on natural grasslands, and innovate the development model of animal husbandry.

(3) The contradiction between grass and livestock should be alleviated and the ecological function of grasslands should be improved. Overgrazing of grasslands is a serious problem in Northern China, and also an important cause of grassland degradation. Giving priority to protection, we are supposed to adopt some grassland management measures and techniques such as grazing prohibition, rest grazing, reducing grazing, rotational grazing, and rotational mowing and fallow according to the degradation degree and utilization of grasslands, so as to fundamentally alleviate the pressure of long-term overgrazing of grasslands. This is an important way to relieve the contradiction between grass and livestock, accelerate the natural recovery and self-healing of the degraded ecosystem, and improve its ecological function. For example, the Inner Mongolia Autonomous Region began to conceive of spring rest grazing in 2001, implementing 30 to 60 days of rest grazing every year from April to May during the period of grass returning to green, so as to accelerate the restoration of degraded grasslands. This measure has been widely promoted in Inner Mongolia, Qinghai, Tibet, and other provinces and regions. The grassland degradation in some areas where the spring rest grazing has been conducted for a long time has been improved obviously. In 2020, Heilongjiang decided to forbid grazing for seven months (April 15–November 15) in 17 counties (cities and districts) to further explore the influence of grazing prohibition on grassland ecological restoration and promote the transformation development of animal husbandry.

(4) Scientific restoration strategies should be formulated according to the degree and characteristics of grassland degradation. The grasslands in Northern China have been degraded for over 50 years since the 1970s. About 90% of the natural grasslands have been degraded in varying degrees, among which more than 60% have been seriously degraded. Therefore, the protection and restoration of grassland ecosystems is a long-term task, and scientific restoration measures should be formulated according to the degree and characteristics of grassland degradation. Especially for the severely degraded grasslands suffering from serious degradation of the ecosystem structure and serious loss of functions, their ecological restoration experiences three key stages, namely vegetation construction, structure optimization, and promotion of function (Fig. 5). ① Vegetation construction. The key scientific and technological problem to be solved is to construct a plant community dominated by pioneer plants and realize the goal of "turning yellow (bare land or sandy land) to green" or "turning black (black soil beach) to green." In this stage, the restoration technology combining biological and engineering measures is needed. ② Structure optimization. The key scientific and technological problems to be solved are to increase the dominant species and their abundance in the primary community significantly, reduce the abundance of pioneer plants, and optimize the structure of plant community by no-tillage reseeding local dominant species. ③ Promotion of function. The scientific and technological goal is to further optimize the structure of plant, soil, and soil biological community, basically achieve close-to-nature restoration, and significantly improve the ecosystem function and stability. It will take a decade or even decades to achieve the restoration goals after getting through these three key stages, especially the restoration of soil and soil biological communities. Therefore, the corresponding technical measures, restoration objectives, and grassland management measures should be formulated according to the characteristics of these three key stages. For instance, while grazing prohibition is necessary in the stage of vegetation construction, its usage is greatly reduced during structure optimization and limited to a rational range during the promotion of function.

(5) The scientific and technological level of forage harvesting and processing should be improved. In China, the growing season of plants in pastoral areas is short, where the

 

winter is long, and the disasters of wind and snow occur frequently. The safe overwintering of brood matron depends largely on the hay harvested in autumn. At present, the technology of forage harvesting, bundling, processing, and storage in pastoral areas in China is backward, and there is a big gap with the countries that are well developed in animal husbandry. During forage harvesting and processing, the loss of crude protein and vitamin caused by prolonged drying time and leaf abscission is very huge. In addition, the poor conditions of storage facilitate the reduction in the quality of forage grass, failing to meet the nutritional and energy needs of brood matron. Correspondingly, it is difficult for grassland animal husbandry to get rid of the extensive and backward management model. Therefore, it is urgent to promote new equipment, technology and techniques of forage harvesting, flattening, bundling, processing, and storage, so as to improve the scientific and technological level of forage grass harvesting and processing, and enhance the edibility of forage grass reserved.

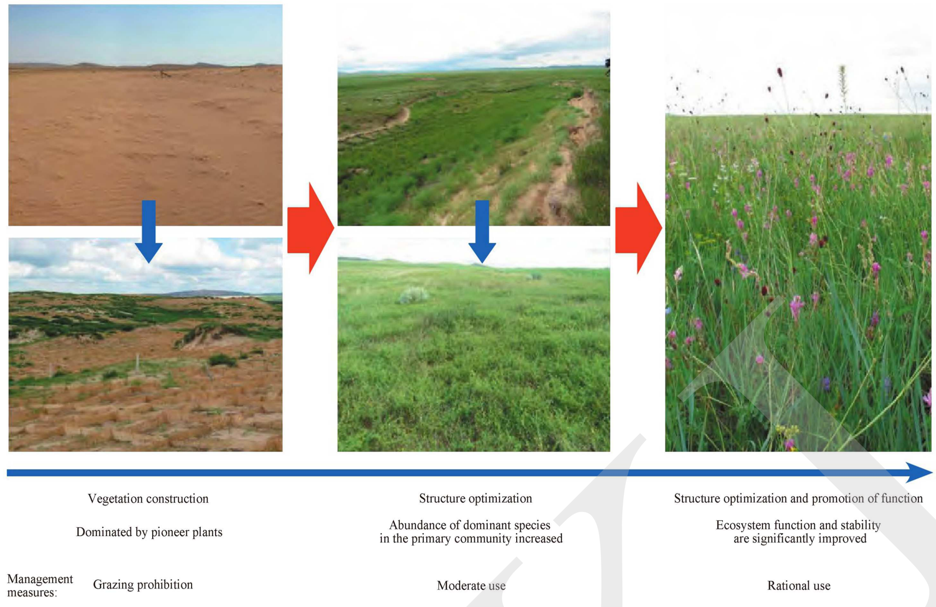


**Fig. 5** Three key stages of ecological restoration of severely degraded grasslands

(6) The source of income of herdsmen should be diversified. We should explore the large-scale business model of family-owned pastures, herdsman associations and herdsman cooperatives suitable for the characteristics of pastoral areas in China, and innovate and improve the system and mechanism of scientific development of pastoral areas in China. At the same time, we should appropriately develop eco-tourism, ethnic culture, and characteristic biological resources and industries to diversify the income source of herdsmen.

(7) The long-term mechanism of subsidies and rewards for grassland ecological protection should be improved. We should raise the standard and prolong the period, so as to achieve the "win-win" results of ecological protection and increase in income for herdsmen by increasing the proportion of ecological protection subsidies and rewards in herdsmen's family income. At the same time, we should establish a strict monitoring, inspection and assessment mechanism to fundamentally curb overgrazing and grassland degradation.

(8) Education should be encouraged to improve the cultural living standard of pastoral areas. Efforts should be made to develop compulsory education, vocational education, higher education, and social undertakings in pastoral areas, so as to continuously improve the quality of population, scientific and cultural level, health level, and quality of life in pastoral areas, realize scientific and technological migration, educational migration and development migration, effectively reduce population pressure in ecologically fragile areas, and promote national unity and social stability.

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**BAI Yongfei** Principle Investigator and PhD Supervisor of Institute of Botany, Chinese Academy of Sciences (CAS), Professor of the University of Chinese Academy of Sciences, and Director of the Inner Mongolia Grassland Ecosystem Research Station, CAS. He won the "Distinguished Young Scholar Program" of the National Natural Science Foundation of China (NSFC) in 2018. He serves as the President of the Plant Ecology Branch of the Chinese Society for Plant Sciences. His main research areas include relationships between biodiversity and multiple ecosystem functions, sensitivity and responses of ecosystem services to global change drivers, and restoration of degraded grasslands and ecosystem management. He has published more than 150 papers in peer reviewed journals, such as Nature, PNAS, Ecology Letters, Ecology, Journal of Applied Ecology, and Global Change Biology. E-mail: yfbai@ibcas.ac.cn

 