Ecological Footprint of Inner Mongolia Grassland Resources and Analysis of Sustainable Utilization: Postprint

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Abstract

Sustainability can be measured through regional ecological footprint levels. Using net primary productivity, the equivalence factors and yield factors for grassland resources in various leagues (cities) of Inner Mongolia were constructed. With each 5-year period as a stage, the ecological footprint of Inner Mongolia's grasslands from 1990 to 2020 was calculated, and the spatial distribution of the ecological footprint was characterized by incorporating population distribution data; on this basis, a land sustainability model was applied to evaluate the sustainability of Inner Mongolia's grassland resources. The results indicate: (1) The yield factors of grasslands in various leagues (cities) of Inner Mongolia vary significantly, generally characterized by higher values in the east and lower values in the west. (2) Ecological carrying capacity also exhibits an east-high, west-low pattern spatially, and the per capita ecological carrying capacity over the 30-year period shows a slight overall declining trend. (3) Per capita ecological footprint increased progressively period by period, shifting from ecological surplus to ecological deficit during 2000–2005. Regions with higher ecological footprints are concentrated in Tongliao City, Xilinhot City, Erenhot City, southern Ulanqab City, and eastern Ordos City. (4) The sustainability of Inner Mongolia's grassland resources declined progressively period by period, degrading from moderate sustainability in 1990 to weak unsustainability in 2020. Regions with severe sustainability degradation are concentrated in Hohhot City, Baotou City, and Wuhai City. The research results aim to provide a reliable theoretical foundation for the sustainable utilization of Inner Mongolia's grassland resources.

Full Text

Preamble

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Ecological Footprint and Sustainable Utilization Analysis of Grassland Resources in Inner Mongolia

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Abstract: Sustainability can be measured through regional ecological footprint levels. This study constructed equivalence and yield factors for grassland resources in each league (city) of Inner Mongolia using net primary productivity. Taking five-year intervals as one period, we measured the ecological footprint of grassland resources in Inner Mongolia from 1990 to 2020 and characterized the spatial distribution of ecological footprint using population distribution data. Based on this, we evaluated the sustainability of grassland resources in Inner Mongolia using a land sustainability model. The results show that: (1) The yield factors of grassland in each league (city) of Inner Mongolia vary significantly, generally showing a pattern of high in the east and low in the west. (2) Ecological carrying capacity also exhibits an east-high, west-low spatial pattern. Only three leagues (cities) in the eastern region (Hulunbuir, Xing' an League, Chifeng City, and Tongliao City) have yield factors greater than 1 and the highest ecological carrying capacity. (3) Per capita ecological carrying capacity shows a slight overall decline, while per capita ecological footprint increases period by period, shifting from ecological surplus to ecological deficit between 2000 and 2005. Regions with high ecological footprint are concentrated in Tongliao City, Xilinhot City, Erenhot City, southern Ulanqab City, and eastern Ordos City. (4) The sustainability of grassland resources in Inner Mongolia declines period by period, degrading from moderate sustainability in 1990 to weak unsustainability in 2020. Areas with severe sustainability degradation are concentrated in Hohhot City, Baotou City, and Wuhai City. The research results aim to provide a reliable theoretical basis for the sustainable utilization of grassland resources in Inner Mongolia.

Keywords: ecological footprint; ecological carrying capacity; sustainable de-

velopment; grassland resources; Inner Mongolia

1. Study Area Overview

Inner Mongolia Autonomous Region (97°12 ~126°04 E, 37°24 ~53°23 N) is located in northern China, with a total area of 1.183×10^{6} km^2 and 12 leagues (cities), and a permanent population of 24.0×10^{6}. The landform is dominated by plateaus, with a temperate continental monsoon climate characterized by large annual temperature fluctuations (0~8°C), low and uneven precipitation (50~450 mm), decreasing from east to west. The region has rich land resources, including forests, grasslands, croplands, deserts, rivers, and lakes, with grassland occupying the largest proportion. From east to west, meadow steppe, typical steppe, desert steppe, and steppe desert are distributed (Fig. 1).

2.1 Data Sources and Processing

All statistical data in this study were obtained from the *China Statistical Yearbook*, *Inner Mongolia Statistical Yearbook*, and EPS data platform (https://www.epsnet.com.cn/). Global average yield data were sourced from the Food and Agriculture Organization database (http://www.fao.org/). Land use and population density data were obtained from the Chinese Academy of Sciences Resource and Environmental Science and Data Center (http://www.resdc.cn/). The land use source data had a spatial resolution of 30 m and a secondary classification level, which was reclassified in ArcGIS into primary land categories: cropland, forestland, grassland, water bodies, construction land, and unused land. Inner Mongolia net primary productivity (NPP) data were derived from EOS/MODIS NPP products with a spatial resolution of 1 km. Since MODIS NPP data from the same series were missing before 2000, we used http://lpdaac.usgs.gov for calculations.

2.2.1 Construction of Equivalence and Yield Factors

The construction of equivalence and yield factors is scale-dependent. Many scholars have localized these factors for different research scales, developing models such as "national hectare," "provincial hectare," and "city hectare" with decreasing applicability scales. Considering the vast territory of Inner Mongolia and the differences in grassland biological productivity among various leagues (cities), we constructed league (city)-level equivalence and yield factors based on the "city hectare" model to improve the accuracy and credibility of ecological footprint accounting. For this single grassland type ecological footprint study, we constructed equivalence and yield factors for grassland. To eliminate differences in ecological productivity between grassland and other land types, we built equivalence factors for grassland in each league (city) to convert grassland ecosystem areas into effective land areas comparable with other land types' biological productivity. To eliminate differences in grassland ecological productivity among regions, we constructed yield factors for grassland in each league (city).

Using the ArcGIS platform, we partitioned each league (city) by land use type, calculated the NPP of various biologically productive lands and their area-weighted sums, and obtained equivalence and yield factors. The formulas are as follows:

$$r = \frac{\mathrm{NPP}_{\text{grassland}}}{\sum_{j=1}^{n}(A_j \times \mathrm{NPP}_j)}$$

$$y = \frac{\mathrm{NPP}_{\text{grassland}}}{\mathrm{NPP}_{\text{grassland, global}}}$$

where r is the equivalence factor; $\mathrm{NPP}_{\text{grassland}}$ is the average NPP of grassland in a league (city); NPP_j is the average NPP of land type j in that league (city); A_j is the area proportion of land type j; y is the yield factor; and $\mathrm{NPP}_{\text{grassland, global}}$ is the global average NPP of grassland.

2.2.2 Ecological Footprint Model

Ecological footprint refers to the biologically productive land area required to supply certain resources to human society while absorbing waste, which is important for judging environmental sustainability. Ecological carrying capacity refers to the optimal service level an ecosystem can achieve under certain environmental conditions to ensure normal biological activity, including the population size, resource consumption level, and economic development intensity it can support. The difference between ecological footprint and ecological carrying capacity is the ecological deficit. A negative difference indicates ecological surplus, meaning the ecological environment can operate healthily; a positive difference indicates a deficit state, meaning the ecological environment is in crisis. The model formulas are as follows:

$$ef = \sum_{i=1}^{n} \frac{c_i}{p_i}$$

$$ec = a \times r \times y$$

$$EF = ef \times N$$

$$EC = ec \times N$$

$$ED = EF - EC$$

$$EF_s = ef \times P$$

$$EC_s = ec \times P$$

$$ED_s = EF_s - EC_s$$

where ef is per capita ecological footprint; i is grassland product category; c_i is per capita annual consumption of product i; p_i is global average annual yield of product i; ec is per capita ecological carrying capacity; a is per capita grassland area in a league (city); EF is total regional ecological footprint; EC is total regional ecological carrying capacity; N is regional population; ED is total regional ecological deficit; EF_s is total ecological footprint per km^2; EC_s is total carrying capacity per km^2; P is population per km^2; and ED_s is ecological deficit per km^2. According to World Commission on Environment and Development recommendations, 12% of ecological carrying capacity should be excluded for biodiversity protection.

Applying the ecological footprint model to grassland requires constructing an integrated resource consumption account for major grassland products in the study area. Referencing existing grassland biological resource accounts in ecological footprint studies and considering data availability and continuity, we established a grassland biological resource account including meat (beef, mutton), wool, and milk for ecological footprint calculation. Based on per capita ecological footprint in each league (city) and combined with population density data, we spatialized ecological footprint and ecological carrying capacity at 1 km^2 scale (formula 8) to obtain spatialized ecological deficit results.

2.2.3 Evaluation of Sustainable Utilization of Grassland Resources

Referencing Zhao Xingguo et al., we used ecological footprint and ecological carrying capacity to construct the Land Use Sustainability Coefficient (LUSC), which is also applicable to single land types. The formula is:

$$\text{LUSC} = \frac{ec}{ef + ec}$$

From equation (9), when $0 < \text{LUSC} < 1$, larger values indicate that environmental carrying capacity is more sufficient to supply resource demand, meaning higher regional land sustainability; smaller values indicate that resource consumption dominates, meaning higher land unsustainability. Referencing existing studies, we divided grassland sustainability into nine levels (Table 1).

Table 1 Sustainability classification of land use

Sustainability Level	LUSC Range
Extremely strong sustainability	$0.9 < \text{LUSC} < 1.0$
Strong sustainability	$0.8 < \text{LUSC} \leq 0.9$
Moderate sustainability	$0.7 < \text{LUSC} \leq 0.8$
Weak sustainability	$0.6 < \text{LUSC} \leq 0.7$
Weak unsustainability	$0.4 < \text{LUSC} \leq 0.6$
Moderate unsustainability	$0.3 < \text{LUSC} \leq 0.4$
Strong unsustainability	$0.2 < \text{LUSC} \leq 0.3$
Extremely strong unsustainability	$0.1 < \text{LUSC} \leq 0.2$
Critical unsustainability	$0.0 < \text{LUSC} \leq 0.1$

Note: LUSC is the Land Use Sustainability Coefficient. The same below.

3.1 Grassland Equivalence and Yield Factors by League (City)

The equivalence and yield factors of grassland in each league (city) are shown in Table 2. Ordos City has the highest grassland equivalence factor, while Hulunbuir City has the lowest. Equivalence factors vary little among leagues (cities), with a coefficient of variation of 6.96%. Hulunbuir City has the highest yield factor, while Wuhai City has the lowest. Yield factors vary significantly among leagues (cities), with a coefficient of variation as high as 48.14%.

Table 2 Equivalence factor and production coefficient of grassland in cities

League (City)	Equivalence Factor	Yield Factor
Hohhot	0.47	0.54
Baotou	0.45	0.67
Wuhai	0.42	0.19
Chifeng	0.53	1.21
Tongliao	0.55	1.35
Ordos	0.61	0.73
Hulunbuir	0.38	1.68
Ulanqab	0.49	0.58
Bayannur	0.46	0.42

League (City)	Equivalence Factor	Yield Factor
Xilingol	0.52	1.12
Alxa	0.43	0.31
Xing' an	0.56	1.47

3.2 Spatiotemporal Pattern of Grassland Ecological Footprint in Inner Mongolia

From 1990 to 2020, the per capita ecological footprint of grassland resources in Inner Mongolia increased period by period, from 0.47 $hm^2 \cdot person^{-1}$ to 3.54 $hm^2 \cdot person^{-1}$, with an average annual growth rate of 13.16% (Fig. 2). The growth rate was fastest during 2000–2005, with an average annual growth rate of 16.94%. Most leagues (cities) showed fluctuating upward trends in per capita ecological footprint (Xilingol, Alxa, Wuhai, Baotou, Ordos, Ulanqab), while Chifeng, Bayannur, Xing' an, and Tongliao showed continuous increases, and Hohhot and Hulunbuir first increased then decreased (Fig. 2). Among all leagues (cities), Xilingol League had the highest grassland ecological footprint, increasing from 2.12 $hm^2 \cdot person^{-1}$ to 13.28 $hm^2 \cdot person^{-1}$, with an average annual growth rate of 6.96%. Wuhai City had the lowest and most stable ecological footprint. Spatialization results show that most leagues (cities) had low grassland ecological footprints with small changes, while areas with high and significantly changing ecological footprints were mainly concentrated in Tongliao City, Xilinhot City, Erenhot City, southern Ulanqab City, and eastern Ordos City and their surrounding areas (Fig. 3).

3.3 Spatiotemporal Pattern of Grassland Ecological Carrying Capacity in Inner Mongolia

From 1990 to 2020, the per capita ecological carrying capacity of grassland resources in Inner Mongolia decreased slightly period by period, from 1.92 $hm^2 \cdot person^{-1}$ to 1.67 $hm^2 \cdot person^{-1}$, with an average annual decline rate of 0.46% (Fig. 4). Among all leagues (cities), Xilingol League had the highest per capita carrying capacity, decreasing from 10.58 $hm^2 \cdot person^{-1}$ to 8.12 $hm^2 \cdot person^{-1}$, with an average annual decline rate of 0.75%. Wuhai City had the lowest per capita carrying capacity with minimal change, decreasing from 0.09 $hm^2 \cdot person^{-1}$ to 0.04 $hm^2 \cdot person^{-1}$, with an average annual decline rate of 2.48%. Areas with high ecological carrying capacity were mainly concentrated in eastern leagues (cities) such as Hulunbuir, Xing' an, Tongliao, and Chifeng (Fig. 5).

3.4 Spatiotemporal Pattern of Grassland Ecological Deficit in Inner Mongolia

From 1990 to 2020, the per capita ecological deficit of grassland resources in Inner Mongolia continuously increased (the numerical value of deficit became more negative). The per capita ecological deficit was -1.45 $hm^2 \cdot person^{-1}$ in 1990 and 1.87 $hm^2 \cdot person^{-1}$ in 2020 (Fig. 6). The fastest change in ecological deficit occurred during 2000-2005, when the status shifted from ecological surplus to ecological deficit. The proportion of grassland area in deficit status gradually increased from 16.67% to 83.33%. Areas with high and stable ecological surplus were mainly concentrated in Hulunbuir City and northern Xilingol League. Areas with high and increasing ecological deficit were mainly concentrated in southern Ulanqab City, eastern Ordos City and its surrounding areas, and southern Xilingol League (Fig. 7).

3.5 Evaluation of Sustainable Utilization of Grassland Resources in Inner Mongolia

The LUSC of grassland resources in Inner Mongolia decreased period by period, with grassland gradually shifting from sustainable to unsustainable states. Grassland showed sustainability in 1990, moderate sustainability during 1995-2000, and weak sustainability during 2005-2010 (LUSC 0.4-0.6). In 2015-2020, grassland shifted to a weak unsustainable state (LUSC 0.3-0.4). The sustainability of grassland in most leagues (cities) generally weakened (Fig. 8). In 1990, all leagues (cities) showed sustainable states, but by 2020, three leagues (cities) showed unsustainable states, with the smallest change in Alxa League where the LUSC decreased by 0.11.

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4. Discussion

The yield factors of grassland resources in Inner Mongolia' s leagues (cities) vary significantly, showing an overall pattern of high in the east and low in the west, consistent with Li Yiming et al.' s findings, indicating obvious quality differences in grassland resources across the region. Similar to yield factors, ecological carrying capacity also shows an east-high, west-low pattern. Only three leagues (cities) in the east (Hulunbuir, Xing' an, Chifeng, and Tongliao) have yield factors greater than 1 and the highest ecological carrying capacity. This is because suitable climatic conditions in the eastern region support high-quality meadow steppe and typical steppe, resulting in higher yield factors and ecological carrying capacity. Leagues (cities) with yield factors less than 1 and lowest ecological carrying capacity are distributed in western desert steppe areas (Alxa, Bayannur, and Wuhai). In Wuhai City, serious grassland resource degradation due to long-term mining development has led to the lowest yield factor and ecological carrying capacity.

From a temporal perspective, the ecological deficit of grassland resources in the region deepened continuously from 1990 to 2020. Due to ecological footprint and its change rate being much greater than ecological carrying capacity (Fig. 2), the status shifted from ecological surplus to ecological deficit between 2000 and 2005 (Fig. 6). The deficit deepening rate slowed after 2010, likely due to the dual effects of economic development and policy regulation. The implementation of the Western Development Strategy accelerated economic development, increasing animal husbandry production and consumption, making ecological footprint growth more pronounced during this period. After 2011, grassland protection policies such as the Grassland-Livestock Balance Management Measures were introduced, and grassland resources began implementing grazing bans and rest periods. Although ecological restoration has inherent lag effects, the grassland ecological carrying capacity began to increase in 2015, while the deficit deepening rate accelerated again due to increased grassland production pressure from land use changes. In recent years, considerable grassland area in Inner Mongolia has been occupied by industrial and mining land and urban land, causing grassland fragmentation that reduces available grassland area for herders, increases grazing intensity, and leads to gradually decreasing ecological footprint.

From a spatial perspective, areas with high ecological footprint are concentrated in economically developed and densely populated leagues (cities), consistent with Chen Xiaojie et al.' s findings on Wuhan urban agglomeration. This occurs because economic development affects population distribution, which in turn affects the spatial distribution of ecological footprint. In this study, grassland resources with high ecological footprint are mainly concentrated in Xilinhot City, Erenhot City, Tongliao City, southern Ulanqab City, and eastern Ordos City and their surrounding areas (Fig. 3). Xilinhot City is the administrative center of Xilingol League, Erenhot City is one of the most important customs ports in Inner Mongolia, Tongliao City has developed agriculture, and Ulanqab City and eastern Ordos City have developed industry and mining with prosperous economies. Multiple factors drive concentrated population distribution in these areas. Among all leagues (cities), Xilingol League, as Inner Mongolia' s most important animal husbandry base, has both the highest ecological footprint and ecological carrying capacity. Xilingol League' s grassland ecological footprint briefly decreased during 1995-2000, while ecological carrying capacity declined significantly during this period, possibly related to accelerated urbanization from the Western Development Strategy. After 2000, a series of grassland protection policies such as "enclosure and grazing ban" were implemented, but ecological restoration has inherent lag effects, so the region' s grassland carrying capacity continued to decline, though the rate slowed after 2015.

Inner Mongolia' s grassland resources require focused attention on sustainability degradation areas concentrated in Bayannur City, Ulanqab City, Wuhai City, Tongliao City, and the Hohhot-Baotou-Ordos economic zone (Fig. 9). Bayannur City and Ulanqab City are distributed in steppe desert and desert steppe zones, where grassland quality is poor, greatly affected by climate factors such as rainfall, with fluctuating grassland productivity and fragile ecological environments. Mineral development in Ulanqab City has also caused serious environmental damage. Wuhai City, as a typical resource-based city, has resource development and industrial development as important pollution sources. Since being established as a characteristic economic circle of Inner Mongolia in 2000, the Hohhot-Baotou-Ordos region has experienced resource development speeds far exceeding other leagues (cities), bringing population growth, industrial pollution, and land resource occupation, causing more serious grassland sustainability degradation in this region. Tongliao City, focusing on agriculture, has inadequate grassland resource protection and serious grassland degradation, affecting sustainability.

Besides economic and population factors, many issues remain for sustainable development of Inner Mongolia' s grassland resources. Extensive and backward management models in pastoral areas and unreasonable industrial structures increasingly consume grassland resources. First, policy support is the fundamental reason affecting grassland resource quality, as standards for grassland-livestock balance subsidies and grazing ban subsidies vary by region. Ensuring grassland resource sustainability requires modernizing pastoral areas, focusing on introducing and developing animal husbandry technology to transform inefficient production into efficient production. Second, reasonable industrial structures and diverse industry types can reduce grassland resource production pressure. Finally, policy support is the prerequisite and foundation for these measures. Increasing policy funding and refining investment standards to ensure policies effectively support relevant departments and personnel is the basic guarantee for implementing these measures. Improving the current sustainability status of grassland resources in Inner Mongolia requires addressing both symptoms and root causes to ensure healthy and sustainable grassland resource development.

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5. Conclusions

1. The yield factors of grassland in Inner Mongolia' s leagues (cities) vary significantly, showing an east-high, west-low spatial pattern.
2. The ecological footprint of grassland resources in Inner Mongolia shows an overall upward trend, shifting from ecological surplus to ecological deficit between 2000 and 2005. Regions with high ecological footprint are concentrated in Tongliao City, Xilinhot City, Erenhot City, southern Ulanqab City, and eastern Ordos City and their surrounding areas.
3. The ecological carrying capacity of grassland resources in Inner Mongolia shows a slight overall decline, continuously decreasing from 1990 to 2015 but turning to increase after 2015. Regions with high ecological carrying

capacity are mainly concentrated in Hulunbuir, Xing' an, Tongliao, and Chifeng leagues (cities).

4. The sustainability of grassland resources in Inner Mongolia declines period by period, degrading from moderate sustainability in 1990 to weak unsustainability in 2020. Areas with severe sustainability degradation are concentrated in Bayannur City, Ulanqab City, Wuhai City, Tongliao City, and the Hohhot-Baotou-Ordos economic zone.

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