Postprint: Construction of Xinjiang Grassland Ecosystem Health Evaluation System

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Abstract

Grassland is an important type of terrestrial ecosystem, and grassland ecosystem health assessment constitutes a crucial component of grassland health research in arid regions. Xinjiang is located in the Central Asian arid region, where the natural grasslands nurtured by the typical "mountain-basin" topographic structure exhibit distinct vertical zonation, and diverse water-heat combinations have formed rich and varied grassland types. This makes grassland ecosystem health assessment in Xinjiang a systematic and complex undertaking, urgently requiring the construction of a grassland ecosystem health assessment system applicable to Xinjiang. This study takes the Xinjiang grassland ecosystem as the research object, constructs an overall framework for Xinjiang grassland ecosystem health assessment, and elaborates the Xinjiang grassland ecosystem health assessment system from the perspectives of data sources and assessment methods. A fundamental database for grassland ecosystems was established based on grassland quadrats, biometeorological, and multi-source remote sensing data. Regarding grassland health assessment methods, assessment objectives were clarified, assessment areas and reference systems were determined, assessment indicators were subsequently screened, and finally grassland health assessment was conducted by selecting assessment methods. The assessment results were categorized into healthy, sub-healthy, alert, and collapsed using the quartile method. This system was applied to conduct grassland ecosystem health assessment in Minfeng County, Hotan Prefecture, Xinjiang. The results showed that temperate desert grassland inside the fence was in a healthy state, while temperate desert grassland outside the fence was in a sub-healthy state. By constructing the Xinjiang grassland ecosystem health assessment system, this study can provide references for grassroots grassland departments to conduct grassland ecological health assessments and promote sustainable grassland development.

Full Text

Evaluating Ecosystem Health in the Grasslands of Xinjiang

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Abstract

Grasslands represent a vital terrestrial ecosystem type, and evaluating grassland ecosystem health constitutes an essential component of grassland health research in arid regions. Xinjiang, located in the arid zone of Central Asia, features a distinctive "mountain-basin" topographic structure that nurtures natural grasslands with pronounced vertical zonality. Moreover, diverse hydrothermal combinations have created a rich variety of grassland types, making ecosystem health assessment in Xinjiang a systematic and complex undertaking that urgently requires a tailored evaluation framework. This study constructs an overall framework for Xinjiang grassland ecosystem health assessment, elaborating on data sources and evaluation methodologies. The framework establishes a foundational ecological geographic database for grasslands based on quadrat surveys, biometeorological data, and multi-source remote sensing. The evaluation process involves clarifying objectives, delineating assessment areas and reference systems, screening indicators, and selecting appropriate evaluation methods. Results are classified into four categories—healthy, sub-healthy, vigilant, and collapsed—using the quartile method. A case study in Minfeng County, Hotan Prefecture, demonstrated that fenced temperate desert grasslands exhibited healthy status, while unfenced areas showed sub-healthy conditions. This evaluation system provides a reference for grassland departments at the grassroots level and promotes sustainable grassland development.

Keywords: grassland; grassland ecosystem; health assessment; remote sensing; geographic information system; Xinjiang

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Introduction

Grasslands serve as crucial ecosystem types with diverse ecological and economic functions, playing significant roles in biodiversity conservation and carbon sequestration. A healthy grassland ecosystem exhibits vitality, maintains its organizational structure, preserves self-regulating capacity, and demonstrates resilience to external pressures. Grassland ecosystem health is intimately linked to human sustainable development, providing continuous and robust ecosystem services essential for human survival and wellbeing. Consequently, grassland health represents a vital component of natural ecosystem health that directly impacts human societal health and safety, where grassland health equates to the sustainability of grassland ecosystems. In the arid regions of northwestern China, grassland ecosystem health assessment is particularly critical for monitoring grassland degradation.

Grassland health evaluation research has evolved through four stages: embryonic, pioneering, mature, and practical phases. Methodologies have progressed from single-factor listing and single-factor composite approaches to functional evaluation and interface process assessment. With the introduction of spaceborne observation technologies, assessments have expanded from plot scales to regional scales. Building upon big data, evaluation indicators have shifted from single to multiple metrics, enhancing the precision and spatiotemporal scale of grassland health assessment. While domestic research on grassland health evaluation has produced notable results, studies have concentrated primarily in the Inner Mongolia Autonomous Region, Ningxia Hui Autonomous Region, Gansu Province, and the Qinghai-Tibet Plateau.

Xinjiang ranks among China' s major pastoral regions, with a grassland area of 5.73$\times 10^{7}$ hm^2 encompassing 11 grassland classes, 25 grassland groups, and 86 grassland types. Grasslands constitute both the main body of Xinjiang' s ecosystem and a critical ecological barrier, while also serving as fundamental production resources for pastoral communities and specific habitats for numerous rare flora and fauna. Although studies by Liu et al., Lu et al., and Du et al. have evaluated grassland health in the Ebinur Lake Basin, Bayinbulak, and Changji Hui Autonomous Prefecture respectively, research targeting the entire Xinjiang region for grassland industry departments remains limited, particularly regarding comprehensive grassland ecosystem health assessment.

In recent years, climate change coupled with unreasonable cultivation and utilization has caused varying degrees of degradation across Xinjiang' s grasslands. Timely and accurate prediction of grassland health status is not only essential for ecosystem health assessment but also fundamental for understanding how grassland ecosystem structure and function sustain the natural environment upon which humans depend. Therefore, this study aims to construct a Xinjiang grassland ecosystem health evaluation system encompassing multi-source data, methodological procedures, overall framework, and development trends. The system integrates grassland bio-meteorology, hydrothermal flux, ground sampling, and multi-source remote sensing imagery to generate a foundational ecological geographic database, screen multi-level and multi-factor indicators, and objectively evaluate grassland ecosystem health status in Xinjiang.

1. Data Sources

Conducting grassland ecosystem health evaluation first requires obtaining reliable ecological geographic data. The type, quantity, and richness of basic data and information resources within the evaluation area directly enhance the quality and accuracy of assessments. A unified approach to compiling and collecting diverse biological, meteorological, hydrothermal flux, ground quadrat sampling, and multi-source remote sensing data of different sources, types, scales, and formats establishes the foundational ecological and geographic database for the evaluation area.

1.1 Bio-meteorological and Hydrothermal Flux Datasets Bio-meteorological and hydrothermal flux data primarily include: air temperature, precipitation, radiation, evapotranspiration, wind speed, wind direction, hydrology, topography, and soil data. Collected data are processed to form spatiotemporal datasets of grassland bio-meteorology and hydrothermal flux, which are then rasterized into appropriate input formats for grassland health evaluation models to support model operation and validation.

1.2 Field Station Observations and Quadrat Survey Datasets Within the evaluation area, grassland ecological monitoring data are collected and compiled, including existing grassland community indicators. Field surveys document vegetation coverage and plant height in quadrats, identify dominant plant species and biomass changes, measure total fresh grass yield, air-dried grass yield, edible fresh grass yield, and edible dry grass yield. Soil samples from quadrats are analyzed for moisture and nutrients, while toxic weeds, their population distribution, and succession patterns are investigated.

1.3 Multi-source Remote Sensing Datasets Commonly used remote sensing data sources for grasslands include AVHRR, MODIS, Landsat, and Sentinel series. Depending on evaluation objectives, high-resolution remote sensing imagery for the assessment area can be obtained or low-altitude unmanned aerial vehicle (UAV) imagery can be collected. Specific products include: - **AVHRR**: Normalized Difference Vegetation Index (NDVI) products with daily temporal resolution and 500 m spatial resolution - **Landsat**: Multispectral and thermal infrared bands with various spatial resolutions (see Table 1) - **MODIS**: Standard land products including surface reflectance, land surface temperature, land cover, vegetation indices, leaf area index, primary productivity, etc. (see Table 2)

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2. Evaluation Methods

2.1 Clarify Evaluation Objectives Grassland ecosystem health evaluation must consider four hierarchical levels—ecosystem, community, population, and individual—to comprehensively reflect biological traits (living components) supplemented by physical and chemical properties such as light, temperature, hydrology, and soil (non-living components), thereby maximizing comprehensive, authentic, and objective assessment. Within specific spatiotemporal scopes, grassland ecosystem health evaluation presents challenges including indicator selection and quantification, spatiotemporal scale limitations, and data accuracy and validity. Different evaluation objectives have distinct emphases requiring targeted indicator selection. Therefore, before conducting health assessments, specific objectives must be clarified, whether focusing on biological components, abiotic components, or ecosystem functions (ecosystem services), to ensure selected indicators are operational.

2.2 Determine Evaluation Area and Reference System **2.2.1 Determine Grassland Health Evaluation Area** Delineating the evaluation area represents the first step in grassland health assessment. Based on evaluation objectives and considering grassland plant characteristics and surface environments, assessment areas can be determined using: (1) administrative divisions, (2) soil and topography, (3) grassland classification systems, (4) grassland regionalization and zoning, or (5) comprehensive combinations of these criteria. Xinjiang comprises 4 prefecture-level cities, 5 autonomous prefectures, 5 prefectures, and 11 county-level cities directly under the autonomous region, totaling 98 county-level units (Table 3). A complete grassland ecosystem evaluation area typically features consistent topography, geomorphology, hydrothermal combinations, and landscape types with similar vegetation and management characteristics.

2.2.2 Determine Reference Area (System) The reference system constitutes another crucial factor in grassland health evaluation. Typically, any grassland ecosystem with known health status can serve as a reference system—a stable state achieved through coordination and balance with local environmental conditions, particularly climate. Reference systems meeting all or key criteria for ecosystem health include: vitality (maximum productivity under natural conditions), resilience (stable and sustained recovery capacity), organizational structure (ecosystem structural stability), ecosystem services (sustained service provision), and ecological barrier functions (maintaining adjacent ecosystem health). In practice, reference systems can adopt minimally disturbed grassland ecosystems from adjacent regions.

2.3 Screen Evaluation Indicators Grassland ecosystems comprise relatively independent aboveground and belowground components that interact strongly to regulate energy transfer, material cycling, and information flow. Grassland ecosystem health possesses both natural and social attributes, requiring scientifically selected indicators that fully consider physical and chemical parameters while evaluating ecological status and service functions across individual, population, community, and ecosystem scales. Based on disciplinary attributes, indicators are categorized into three groups: biological characteristics, biophysical characteristics, and ecological function indicators (Table 6). This indicator system references the national standard "Grassland Health Assessment" (GB/T 21439-2008), draws from grassland ecosystem health evaluation methods (Table 7), and incorporates the national standard "Specifications for Assessment of Forest Ecosystem Services" (GB/T 38582-2020).

2.4 Select Evaluation Methods Ecosystem health evaluation has evolved through four stages, with domestic grassland health assessment methods including: VOR index evaluation models, CVOR index evaluation models, analytic hierarchy process, principal component analysis, fuzzy comprehensive evaluation, cluster analysis, and attribute comprehensive evaluation. This study integrates functional evaluation and interface process assessment methods, expands spatiotemporal scales using multi-source remote sensing data, and consolidates grassland ecosystem health evaluation factors (Table 6). To avoid limitations of single methods, we recommend: analytic hierarchy process, VOR comprehensive index model, CVOR evaluation model, and PSR evaluation model, with results classified into four levels (healthy, sub-healthy, vigilant, and collapsed) using the quartile method.

2.4.1 Analytic Hierarchy Process (AHP) AHP is a systematic, hierarchical multi-objective decision-making method combining qualitative and quantitative analysis. Based on indicator properties and overall objectives, the method decomposes indicators into different components and organizes them hierarchically according to relationships and affiliations. For Xinjiang grassland ecosystem health evaluation, the top level (A) is "Xinjiang Grassland Ecosystem Health Evaluation" ; the criterion level (B) comprises selected indicators such as biological characteristics and population status; and the factor level (C) includes specific evaluation factors like aboveground biomass and belowground biomass.

2.4.2 VOR Comprehensive Index Model The VOR model calculates grassland health status through a comprehensive index considering Vigor (V), Organization (O), and Resilience (R). Vigor represents net primary productivity, organization reflects plant community structure, and resilience indicates capacity to maintain structure and function. The calculation is:

$$VOR = \alpha V + \beta O + \gamma R$$

where α, β, and γ are weight coefficients for V, O, and R respectively, satisfying $\alpha + \beta + \gamma = 1$.

2.4.3 CVOR Index Evaluation Model The CVOR model comprehensively considers both biological components and soil environment as the foundation for material and energy exchange. The calculation is:

$$COVR = K_c \times C + K_v \times V + K_o \times O + K_r \times R$$

where Kc, Kv, Ko, and Kr are weight coefficients for Condition (C), Vigor (V), Organization (O), and Resilience (R). The Condition index reflects the interface process between plants and atmosphere—environmental factors affecting ecosystem structure and function. When any individual index value exceeds 1, it is set to 1.

2.4.4 Pressure-State-Response (PSR) Model The PSR model comprises pressure, state, and response layers. The pressure layer describes human activities and natural processes that disturb grassland ecosystems; the state layer reflects ecosystem conditions; and the response layer indicates the degree of ecosystem response to environmental changes. The calculation is:

$$HI = (1 - P) \times S \times R$$

where HI is the comprehensive health index, P is the pressure layer value, S is the state layer value, and R is the response layer value.

2.5 Overall Framework The overall framework for Xinjiang grassland ecosystem health evaluation comprises three components: foundational work, indicator screening, and health assessment (Figure 1). Foundational work focuses on defining spatiotemporal scope, obtaining basic information, clarifying overall objectives, delineating evaluation areas, determining reference systems, and constructing the foundational ecological geographic database. Indicator screening utilizes the established database to select appropriate indicators and build the evaluation index system. The assessment phase involves selecting suitable methods, calculating comprehensive scores, and evaluating ecosystem health status. Finally, corresponding recommendations are proposed for sub-healthy, vigilant, and collapsed conditions.

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3. Case Study: Xinjiang Grassland Ecosystem Health Evaluation System

Xinjiang' s natural grasslands exhibit distinct vertical zonality, with different grassland types developing across latitudes, longitudes, and altitudes due to varying hydrothermal combinations. Assessing grassland health across Xinjiang is complex and challenging. However, advances in computer hardware/software, mobile technology, cloud computing, and artificial intelligence have created new opportunities. This section presents a case study in Minfeng County (Hotan Prefecture) focusing on temperate desert grasslands.

The study area in Minfeng County is located at the northern foothills of the Kunlun Mountains and southern edge of the Taklimakan Desert, with dominant species including *Seriphidium rhodanthum*, *Ceratoides latens*, *Reaumuria soongarica*, and *Ephedra intermedia*. Field surveys were conducted in Yeyike Township, Minfeng County in July 2020, collecting data on vegetation height, coverage, aboveground biomass, and species richness in sample plots (Table 8, Figure 2). Within fenced areas (Plot 1), no grazing occurred, while unfenced areas (Plots 2-4) experienced year-round grazing.

Using the VOR comprehensive index model with weight coefficients $\alpha = 0.4$, $\beta = 0.3$, and $\gamma = 0.3$, aboveground biomass represented vigor (V), vegetation height and coverage represented organization (O), and species richness represented resilience (R). Canopy coverage was derived from DJI Phantom 4 RTK UAV orthoimagery processed in ArcGIS. Vegetation height was measured for dominant species, and aboveground biomass was harvested from 1 m $\times$ 1 m quadrats.

Results showed VOR comprehensive indices of 0.78 for Plot 1 (healthy), and 0.52, 0.49, and 0.51 for Plots 2-4 (sub-healthy) respectively. The healthy status within the fence resulted from vegetation recovery without grazing pressure, combined with regional climate warming and humidification trends that favor grassland growth. Outside the fence, overgrazing and year-round utilization led to degradation signs, with vegetation height, coverage, and biomass all lower than fenced areas, resulting in sub-healthy status.

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4. Future Perspectives

4.1 Interdisciplinary Integration Grassland ecosystem health evaluation should integrate perspectives from geography, economics, ecology, sociology, management, and human health. A comprehensive, objective assessment based on interdisciplinary foundations can explore how human activities and climate change affect grassland ecosystem services and their impacts on regional economies and societies, providing recommendations aligned with sustainable development and ecosystem management objectives.

4.2 Big Data, Cloud Computing, and Deep Learning Future development should focus on building an intelligent monitoring network for Xinjiang grassland health, enabling dynamic monitoring, objective evaluation, and effective early warning. Deep integration with emerging technologies including new-generation information communication, artificial intelligence, and big data will be essential for advancing grassland health assessment capabilities.

4.3 Temporal Continuity and Spatial Expansion Grassland ecosystems represent a continuum where soil, vegetation, and water are interconnected. Extending temporal scales and expanding spatial scope are crucial for health evaluation. Current assessments must objectively analyze historical data to rationally utilize existing resources and make sustainable predictions and strategies for future grassland management. Short-term, small-scale studies cannot fully explain ecosystem evolution or objectively interpret spatiotemporal dynamics.

Grassland health evaluation should expand spatially across individual, population, community, ecosystem, landscape, and regional scales, while extending temporally to enable correct assessment and prediction of current status and trends.

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Figures

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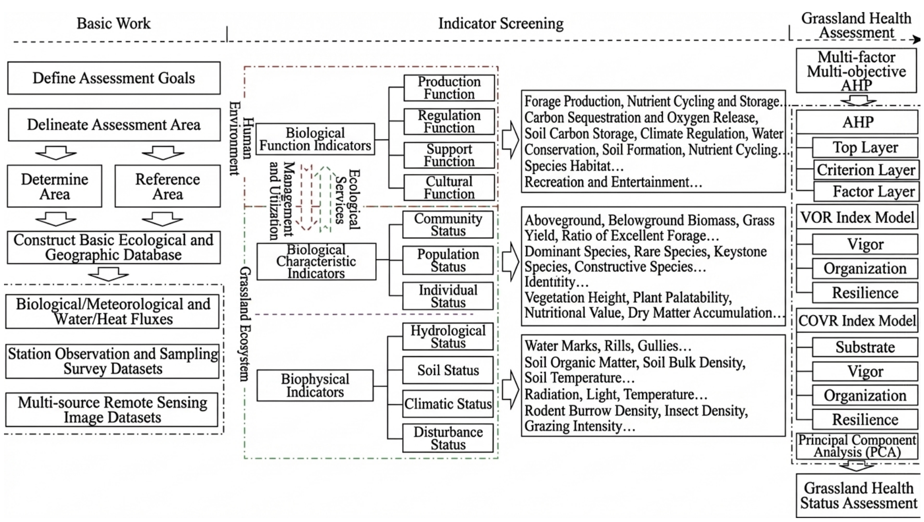

Figure 1: Figure 1