

Article

A 3M Framework for Gross Ecosystem Product Valuation in Natural Protected Areas: Integrating Parameter Localization with Uncertainty Analysis

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Abstract

Natural protected areas harbor ecosystems with significant ecological functions and economic value. The scientific accounting of Gross Ecosystem Product (GEP) is therefore critical for harmonizing ecological conservation with regional development. Using China's Xilingol Grassland National Nature Reserve as a case study, this paper develops and applies a novel "3M" GEP accounting framework, integrating the three core elements of multi-dimensional indicators, multi-source data, and multi-method adaptation. This framework was employed to systematically quantify the values of the reserve's provisioning, regulating, and cultural ecosystem services. The results show an annual GEP of CNY 170.5229 billion for the 5835.65 km² reserve. Regulating services constituted the dominant share (97.77%), with climate regulation being the most significant component (CNY 160.15 billion). It is important to note that this high proportion is method-dependent, stemming from the industrial-substitution scenarios used to value non-market services. The combined contribution of provisioning and cultural services was 2.23%, representing 1.00% and 1.23%, respectively. Uncertainty analysis indicated a total error margin of $\pm 9.3\%$ (95% confidence interval), which is within an acceptable range for ecological accounting. The primary sources of uncertainty were data-resolution limitations, methodological choices, and regional parameter variability. These findings, corroborated by sensitivity analysis, confirm the robustness of the GEP estimate and clarify the influence of key ecological parameters on the valuation. By optimizing regional indicator adaptation, methodological localization, and multi-source data cross-validation, the proposed framework enhances the accuracy and policy relevance of ecosystem service valuation. It thus provides a methodological reference for GEP accounting and ecological asset management in other natural protected areas.



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1. Introduction

Natural protected areas are core components of national ecological conservation. Their primary value lies in the conservation of biodiversity, the sustenance of ecosystem service supply, and the safeguarding of national ecological security, providing essential spatial support for achieving harmony between humans and nature [1,2]. As a vital ecological type

within these areas, grassland ecosystems play an irreplaceable role in maintaining biodiversity, regulating regional climate, conserving water sources, and preventing wind erosion and desertification [3,4]. Consequently, research on the valuation and value realization mechanisms of these ecosystems is central to advancing the synergy between ecological protection and economic development.

As a significant component of the global temperate grassland zone, the temperate grasslands of northern China are characterized by unique climatic conditions and marked ecosystem vulnerability, making their ecological protection and value realization subjects of considerable concern [5,6]. Among them, the Xilingol Grassland National Nature Reserve (hereafter “XG”), China’s first national-level grassland nature reserve, preserves an intact original temperate grassland ecosystem. It serves as a crucial node in the construction of China’s northern ecological security barrier, with its ecological functions directly linked to sandstorm control and sustainable regional development in the Beijing–Tianjin–Hebei area [7]. However, in recent years, the superposition of anthropogenic disturbances—including large-scale wind power construction, expanding mining activities, and traditional overgrazing—has led to ecological issues such as landscape fragmentation, soil degradation, and vegetation deterioration in the Xilingol grassland. Consequently, the “conservation versus development” conflict has become increasingly prominent [8]. Against this backdrop, targeted valuation research using XG as a representative case—one that accounts for the regional heterogeneity of temperate grassland protected areas—can address the reserve’s specific ecological value realization challenges while providing a scientific reference for similar protected areas. This approach holds both theoretical and practical significance.

Ecosystem valuation serves as a critical bridge connecting ecological conservation with economic development [9]. Since the pioneering work by Costanza et al. (1997) [10] on ecosystem service valuation, Gross Ecosystem Product (GEP) has evolved into a core accounting tool for regional ecological asset management, as it comprehensively quantifies the value of final products and services provided by ecosystems. GEP has been widely applied to various ecosystems, including grasslands, forests, and wetlands [11,12].

In the field of grassland ecology, scholars have explored GEP accounting from multiple perspectives. For instance, Ren et al. [13] established a three-dimensional accounting framework for grassland ecological products encompassing provisioning, regulating, and cultural services. This framework clarifies the core dimensions of value composition and provides a foundation for the systematic assessment of grassland ecological assets. Haoriwa [14] introduced methodological refinements, such as more precise spatial analysis units, thereby enhancing the accuracy of estimating certain service values. Li and Qian [15] offered theoretical insights into value realization pathways, discussing mechanisms based on property rights definition and market transactions. Hu et al. [16] expanded application scenarios by linking GEP accounting with the reform needs of the natural resource asset management system, specifically for state-owned grassland resources. Collectively, these studies have preliminarily established a general accounting framework covering provisioning, regulating, and cultural services, making progress in quantification methods, value realization pathways, and asset-based management.

However, existing research still suffers from limitations in regional adaptability and critical synthesis. Specifically: (1) Data Integration: The synthesis of regional data sources requires improvement. For example, in their valuation of windbreak and sand fixation services in the Xilingol grassland, Gao et al. [17] primarily relied on remotely sensed ecological service flow data, with insufficient integration of field-observed data, such as vegetation coverage under drought stress and soil wind erosion modulus. This limitation aligns with the observation by Pergola et al. [18] on the need for stronger field data support in windbreak

and sand fixation accounting for temperate grasslands. (2) Methodological Adaptability: The alignment between accounting methods and a region's core ecological functions requires further optimization. While globally unified indicator systems exist, they often inadequately cover region-specific services [19]. Research also emphasizes the need to incorporate characteristic indicators, such as “nomadic cultural landscape value” and “transboundary ecological barrier function,” into temperate grassland valuation [20]. Furthermore, innovative valuation methods suited to the broad-scale, public-good characteristics of semi-arid grasslands with transboundary sand control functions are still needed. For grasslands where ecotourism is a core cultural service, comprehensive accounting methods that balance ecological carrying capacity and tourism value remain underexplored [21,22]. (3) Indicator System Refinement: Indicator systems can be enhanced to better reflect regional characteristics and achieve multi-dimensional synergy. Empirically, Li et al. [23], in their review of grassland ecosystem service valuation, explicitly noted that most current studies focus on indicators such as forage yield and conventional carbon sequestration, while insufficiently incorporating values specific to temperate grasslands, such as nomadic cultural landscape value and transboundary wind and sand control value. For instance, a representative study on the ecosystem service assessment of the Inner Mongolia grassland by Li X M [23], while comprehensive in evaluating provisioning and regulating services, excluded pastoral or nomadic cultural landscapes from its cultural service indicator system, exemplifying this common omission. Moreover, studies by Sun [24], Guo et al. [25], and Li et al. [26] further note that existing indicators often lack comprehensive coverage of region-specific aspects, such as the habitat maintenance value for endemic species or the water conservation value in wetland grasslands. Methodologically, there is a need to improve the construction of a multi-dimensional synergistic accounting framework that integrates ecological resource support, service value realization, and conservation/restoration safeguards [27]. The lack of clear principles for regionally adapting indicator selection leads to a mismatch between generic indicator systems and the core functions of specific ecosystems.

Against this backdrop, this study proposes a 3M GEP accounting framework grounded in the attributes of temperate grassland nature reserves. Centered on regional heterogeneity adaptation, the framework integrates region-specific indicator guidance, multi-source data synergy, and multi-method adaptation to reconcile the tension between generalizability and specificity. This is achieved through the application of tailored indicators, diverse data sources, multiple methodological approaches, and regionalized parameter calibration. Concurrently, sensitivity and uncertainty analyses are conducted to enhance the reliability of the accounting results.

This paper aims to address the following core research questions:

- (1) How does shifting from generic indicators to region-specific indicators alter the perceived value structure (e.g., the relative dominance of specific regulating services) of a temperate grassland protected area?
- (2) To what extent does the coupling of accounting methods with local product attributes and the use of localized parameters improve the precision and reduce the uncertainty/variation of the GEP estimate compared to using standard/default approaches?
- (3) How does the integration and cross-validation of multi-source data enhance the credibility of GEP accounting results?

2. Materials and Methods

2.1. Research Area and Research Approach

(1) Study Area

The Xilingol Grassland National Nature Reserve (XG), established in 1985, is China's first national-level grassland nature reserve. It was designated as a UNESCO “Man and the

Biosphere Programme” (MAB) Biosphere Reserve in 1987 [28,29]. UNESCO recognizes XG as “the world’s most representative temperate typical steppe—with constructive species including bunchgrasses and rhizomatous grasses such as *Stipa* and *Leymus chinensis*—and the most intact core area preserved in the East Asian subregion of the Eurasian steppe zone” [30]. XG is characterized by three key attributes: it serves as a critical node in the ecological security barrier of northern China [31], possesses outstanding integrity of its pristine grassland ecosystem [32], and faces a prominent conflict between conservation and development. Its climatic conditions—a semi-arid continental climate in the middle temperate zone, with mean annual temperatures of -0.5 to 3.5 °C and precipitation of 200–300 mm—ecosystem diversity (encompassing typical steppe, meadow steppe, sandy land forest, and valley wetlands), and predominant anthropogenic disturbances (e.g., grazing, ecotourism, and resource exploitation) are representative of temperate grasslands both in northern China and worldwide [30].

The reserve is situated on the eastern Inner Mongolia Plateau, with geographical coordinates ranging from $115^{\circ}32'$ to $117^{\circ}12'$ E and $43^{\circ}26'$ to $44^{\circ}33'$ N. It plays an irreplaceable role as a barrier against the southward invasion of wind-blown sand, safeguarding the ecological security of the Beijing–Tianjin–Hebei region and northern China. The total area of the reserve is 583,565.38 hectares. Under a functional zoning plan approved by the State Council in 2020, a two-zone management structure is implemented. The core protection zone (111,710.43 ha) enforces strict ecological controls prohibiting anthropogenic disturbances. The general control zone (471,854.95 ha) permits limited utilization activities, such as sustainable grazing and ecotourism (Figure 1).

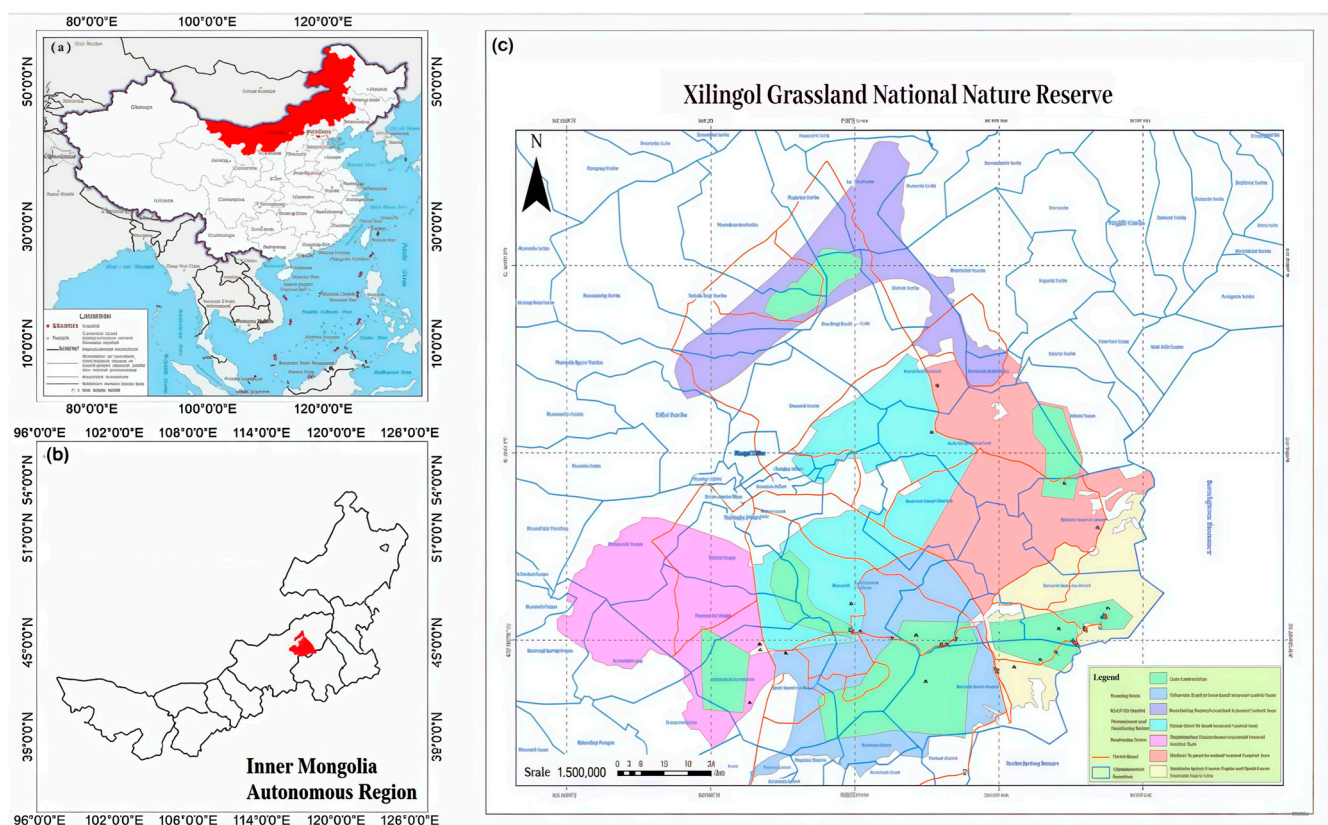


Figure 1. Location and detailed map of Xilingol Grassland National Nature Reserve; (a) regional location in China, (b) location in Inner Mongolia, (c) detailed functional zoning map.

XG was selected as a representative case study due to the close alignment of its ecological characteristics, functional positioning, and research needs. It should be noted that

the GEP accounting results for XG are influenced by local factors, including its specific management system, conservation intensity, and resource endowment, limiting their direct universal applicability. Therefore, to ensure regional adaptability, applying these methods elsewhere requires adjustments to accounting boundaries based on the local management system, modifications to ecological parameters per local conservation intensity, and optimization of value quantification methods considering local resource endowments.

(2) Research Approach

The “3M” GEP accounting framework developed in this study is structured around three core, interactively linked modules. Its key innovation addresses the “adaptation gap” prevalent in existing frameworks by systematically integrating and localizing indicators, data, and methods, as detailed in the following modules.

The Multi-Dimensional Indicator Module establishes a regionally adapted GEP accounting indicator system closely aligned with the ecological and socio-economic context of XG. In contrast to generalized systems, provisioning service indicators are focused on core livelihood outputs from local agriculture (e.g., potatoes, wheat, forage grass) and animal husbandry (e.g., beef, mutton, milk). Forestry and fishery products, which are scarce within the reserve, are excluded to prevent indicator homogenization. Regulating services encompass six core ecological barrier functions: carbon sequestration and oxygen release, water conservation, soil retention, climate regulation, nutrient cycling, and organic matter production. These directly address key regional challenges, including drought stress and wind-sand erosion. Cultural services include landscape aesthetics and ecotourism values reflecting nomadic cultural elements. This delineation clearly defines the scope and priorities of “what to account for,” enhancing region-specificity and avoiding redundancy.

The Multi-Source Data Module strengthens the synergy and field-based calibration of multi-source data. Moving beyond the prevalent reliance on secondary statistical data for valuing material products [28], this study incorporates first-hand field survey data. This approach not only addresses gaps in regionally variable data absent from statistical yearbooks (e.g., spatial price differences for mutton) but also provides primary data for zonal calibration of valuation models. Moreover, field survey data are systematically integrated into the accounting of regulating and cultural services, thereby enhancing the authenticity and relevance of the data inputs.

The Multi-Method Adaptation Module performs valuation through method cross-validation and localized parameter calibration. Unlike the common practice of applying distinct methods to different indicators, the 3M framework employs cross-validation using multiple methods for key indicators. For example, the value of carbon sequestration is evaluated by combining the carbon trading price and benefit-transfer methods, whereas soil conservation value is assessed by comparing the replacement cost and protective expenditure methods. Additionally, the rationality of climate regulation values is examined through counterfactual analysis. All methods are calibrated using regional parameters (e.g., local carbon prices, industrial oxygen production costs) to mitigate bias from generic default values.

Collectively, these three modules form an interactive, closed-loop system of “guidance, support, adaptation, and feedback” (Figure 2). The Indicator Module sets the accounting direction, the Data Module supplies quantitative support, and the Method Module executes value conversion. Sensitivity and uncertainty analyses serve as the feedback mechanism. They are used to examine the sensitivity of key parameters and the robustness of the GEP results, while also providing a basis for optimizing data inputs, methods, and parameters.

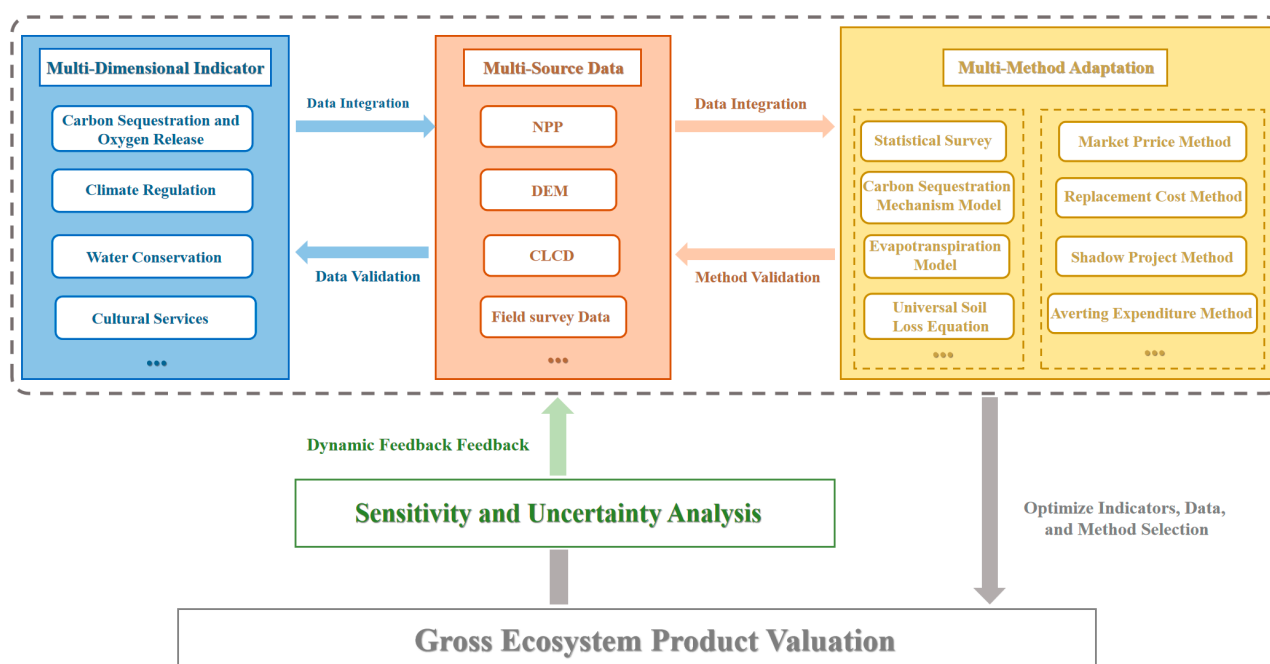


Figure 2. Interaction Mechanism of the 3M Framework.

2.2. Data Sources and Data Preprocessing

(1) Data Sources

This study employed a multi-source data integration approach to support ecosystem value accounting. The data types comprised remote sensing imagery, digital elevation models (DEM), land use data, climate data, soil property data, and local statistical year-books. All data were obtained from open-access datasets or official statistics provided by authoritative domestic and international institutions, which ensured data reliability and standardization. To enhance the local adaptability of accounting indicators and the authenticity of results, field investigations were conducted specifically for indicators related to provisioning and cultural services. Additionally, data cross-validation was performed to optimize rationality and strengthen research validity.

The primary data used are as follows:

Remote Sensing Data: The MODIS NPP product (MOD17A3HGF V6.1) released by NASA was utilized. This product is based on a light use efficiency model, has a spatial resolution of 500 m, and is updated annually. It was used to generate a spatial distribution map of the Net Primary Productivity (NPP) for the reserve in 2024 (details in Figure 3). For the XG area, the NPP values ranged from 127.6 to 471.4 g C/m². Spatially, NPP exhibited a pattern of “decreasing from southeast to northwest.” The NPP level in the core protected area was significantly higher than that in the general control area. Among land cover types, cropland had the highest NPP (302.10 g C/m²), followed by water bodies and hydraulic facilities (276.27 g C/m²) and forest land (275.88 g C/m²). Grassland NPP was relatively lower (259.77 g C/m²). These data provided high-precision spatialized parameters for accounting core services such as carbon sequestration and oxygen release.

Land Use Data: The 2024 China Land Cover Dataset (CLCD) with a 30-m resolution was used, sourced from the National Cryosphere Desert Data Center of China. Grassland is the dominant land cover type in XG, covering 5513.71 km² and accounting for over 94% of the total area. Forest land (160.99 km²) and water bodies (87.40 km²) are secondary land types. The combined area of cropland, land for transportation, and other types accounts for less than 2% and is scattered in distribution.

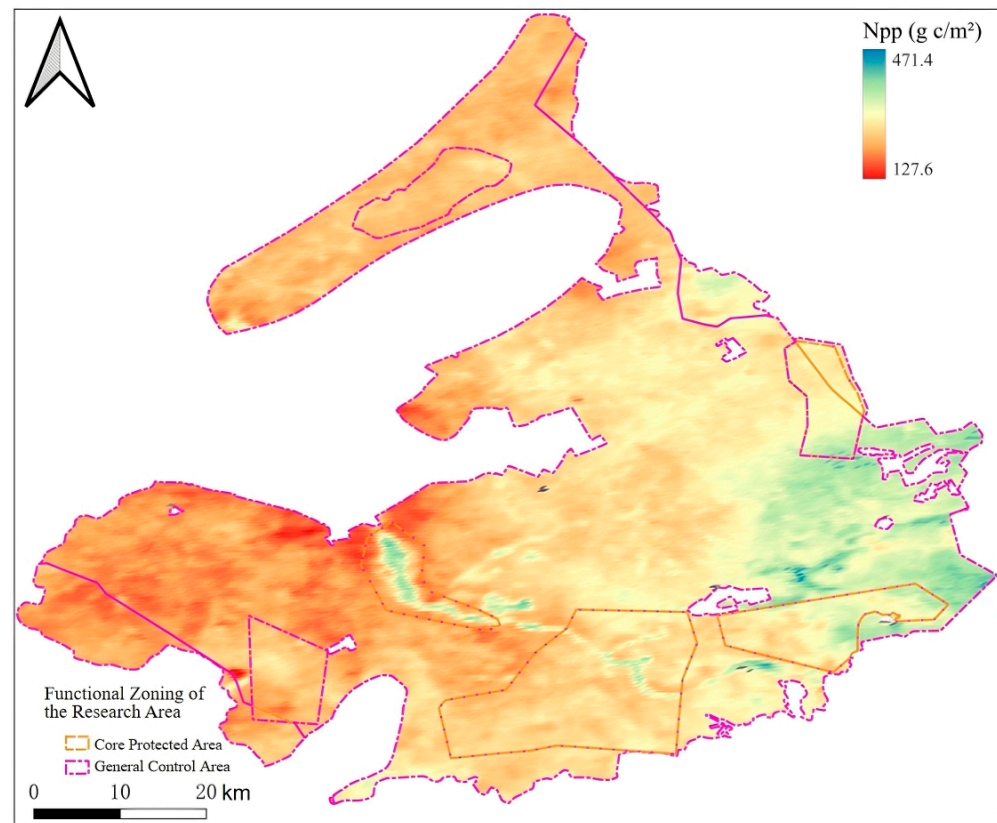


Figure 3. Spatial Distribution Map of NPP in XG.

Climate Data: Precipitation and potential evapotranspiration data were obtained from the National Tibetan Plateau/Third Pole Environment Data Center. The datasets have a 1-km resolution, a monthly temporal scale (1901–2024), and are in NETCDF (.nc) format. Potential evapotranspiration was calculated using the Hargreaves formula, with units of 0.1 mm. The average annual precipitation in the reserve for 2024 was 234 mm (range: 205.1–278.9 mm), showing a spatial pattern of “increasing from northwest to southeast.”

A field survey was conducted from 2 July to 2 August 2025 across nine key administrative units within the Xilingol Grassland National Nature Reserve (XG) in Abag Banner, Inner Mongolia. The surveyed units included Baiyinxile Ranch, Beilike Ranch, Maodeng Ranch, Baiyinkulun Ranch, Bayanbaolage Sumu, Chaokewula Sumu, Baoligen Sumu, Jirengaole Town, and Honggeergaole Town. The survey area encompassed both the core protection zone and the general control zone, covering major ecosystem types—such as typical steppe, meadow steppe, and sandy land forests—to ensure spatial representativeness.

For provisioning services, core data were collected systematically from the nine units, including cultivated/grazing area, annual yield, and local market prices for agricultural products (e.g., potato, wheat), livestock products (e.g., beef, mutton, milk), and forage products. This yielded a regionalized dataset comprising 12 product categories. The regional coefficient of variation for agricultural and livestock product prices ranged from 3.1% to 5.2%, reflecting moderate spatial heterogeneity in the data.

For cultural services, a questionnaire-based survey was administered using a two-stage sampling approach. Twenty-five questionnaires were distributed in each of the nine units; within each unit, a simple random sampling method was used to survey various tourist groups and local residents. The questionnaire covered core dimensions such as travel motivation, willingness to pay (WTP), tourism expenditure, and overall evaluation of the study area. Of the 225 questionnaires distributed, 216 valid responses were obtained, yielding a valid response rate of 96%. The mean WTP was 380 CNY/person

(SD = 118.6 CNY; variance = 14,065.96). The mean per capita tourism expenditure was 531 CNY/person (SD = 132.4 CNY; variance = 17,529.76), with a 95% confidence interval of [514.6, 547.4] CNY/person.

This primary survey data served as the basis for the local calibration of secondary data (obtained from the 2024 Xilingol League Statistical Yearbook) and key accounting parameters. The calibration ensured that the final gross ecosystem product (GEP) accounting results aligned closely with the specific ecological and socio-economic context of the study area.

(2) Data Preprocessing

To ensure the accuracy and reproducibility of ecosystem service accounting and to align with the FAIR (Findable, Accessible, Interoperable, and Reusable) data principles, standardized preprocessing was applied to all multi-source spatial data (Table 1). The procedure was designed to achieve temporal alignment and control errors for the baseline year of 2024, comprising the following specific steps:

First, projection systems were unified. All datasets were projected to the China Geodetic Coordinate System 2000 (CGCS2000) using a 3-degree Gauss–Krüger zone 38 projection (Projection: CGCS2000_3_Degree_GK_Zone_38; Central Meridian: 114° E; Linear Unit: meter; Reference Ellipsoid: CGCS2000). This transformation, performed in ArcGIS Pro (version 3.2), ensured consistent spatial referencing, prevented overlay errors due to projection mismatches, and established a common spatial foundation for subsequent multi-source data integration.

Second, raster resolution standardization. To address heterogeneity in resolution among multi-source raster datasets (e.g., 500 m MODIS NPP, 30 m land use, and 1 km meteorological data), all layers were uniformly resampled to a 500 m resolution to ensure computational consistency. A combined approach was employed: bilinear interpolation for continuous variables (e.g., climate data) and nearest-neighbor resampling for categorical variables (e.g., land use). This balanced accounting accuracy with computational efficiency. Prior to resampling, the 3σ rule was applied to remove statistical outliers, thereby reducing potential error propagation. While standardizing to a 500 m grid facilitates the spatial alignment of multi-source data and improves processing efficiency, the spatial smoothing effect can lead to a local underestimation of service values from small, fragmented, high-value habitats (e.g., patchy wetlands and riparian zones). A comparative validation based on selected typical riparian and wetland patches ($<0.5 \text{ km}^2$ each) within the study area suggested that this resampling process introduces an overall bias of $\leq 5\%$ to the total regional Gross Ecosystem Product (GEP) estimate. For extensive, homogeneous areas like typical steppe, resampling smooths local heterogeneity but preserves the regional vegetation coverage gradient; consequently, the overall valuation bias for services such as climate regulation and soil conservation remains minimal. To mitigate potential local underestimation, a calibration was performed using field-surveyed distribution data for wetlands and riparian zones, ensuring no systematic bias was introduced in valuing these core functional areas.

Table 1. Summary of Data Sources.

No.	Data Name	Data Type	Source Institution	Key Specifications	Data Link/Access Date	Primary Use	Uncertainty
1	MODIS NPP Data	Net Primary Productivity (NPP)	NASA, USA	Spatial resolution: 500 m; Temporal resolution: 1 year; Based on LUE model	Google Earth Engine (GEE) platform, product: MOD17A3HGF V6.1 URL (accessed on 15 August 2025)	Ecosystem productivity assessment; carbon sequestration and oxygen release accounting	The 500 m resolution fails to adequately resolve the heterogeneity of small-patch wetlands and sparse forests on sandy land. In addition, the modeling approach may not accurately reflect the physiological traits of XG's dominant vegetation.
2	SRTM DEM Data	Digital Elevation Model	NASA & NGA, USA	Spatial resolution: 30 m; Vertical datum: WGS84/EGM96	https://earthexplorer.usgs.gov/ URL (accessed on 15 August 2025)	Terrain analysis; slope length and steepness factor calculation	Minor elevation errors exist in flat grassland areas. The influence of micro-topography on soil erosion and water conservation may be underestimated.
3	CLCD Land Use Data	Land Cover Remote Sensing Monitoring	Wuhan University Team, China	Spatial resolution: 30 m; Temporal coverage: 1985–2022	National Cryosphere Desert Data Center: http://www.ncdc.ac.cn URL (accessed on 15 August 2025)	Ecosystem type classification; water conservation and soil retention accounting	Classification ambiguity occurs between sparse grassland and sandy land. Minor discrepancies exist between the CLCD data and the observed land-use changes in XG.
4	Climate Data	Derived Meteorological Observation	National Tibetan Plateau/Third Pole Environment Data Center, China	Spatial resolution: 1 km; Temporal resolution: monthly (1901–2024)	https://data.tpdc.ac.cn/ URL (accessed on 15 August 2025)	Water conservation and climate regulation accounting	The 1-km spatial interpolation introduces local discrepancies in precipitation estimates. The Hargreaves formula exhibits limited suitability for the XG region.
5	Soil Data	Soil Physicochemical Property	1. Nature article 2. FAO/IIASA 3. National Cryosphere Desert Data Center, China	1. Soil depth map: 1 km; 2. HWSD: 1 km; 3. Erodibility factor: 300 m	1. https://www.nature.com/articles/s41597-019-0345-6 2. https://gaez.fao.org/pages/hwsd 3. https://www.scidb.cn/ URL (accessed on 15 August 2025)	Water conservation, soil retention, and nutrient cycling accounting	Spatial resolution mismatch with other data sources results in integration challenges. The EPIC model does not adequately account for the locally high calcium carbonate content characteristic of Kastanozems.
6	Xilingol League Statistical Yearbook	Structured Statistical Data	Statistics Bureau of Xilingol League, China	2024 annual data (agricultural output, livestock output, tourist visits, etc.)	https://tjj.xlgl.gov.cn (2024 data used for material and cultural services accounting)		Potential statistical bias may affect production data for non-centralized livestock products. Tourism data likely overestimates the number of non-ecotourism visitors.
7	Field investigation data	structured data	Baiyinxile Ranch, Beilike Ranch, Maodeng Ranch, Baiyinkulun Ranch, Bayanbaolage Sumu, Chaokewula Sumu, Baoligen Sumu, Jirengaole Town, and Honggeergaole Town in Abag Banner	The cultivated area, yield, and market price of (a) agricultural products (e.g., rice, wheat, corn, soybeans, potatoes, and oilseeds) and (b) grassland products (e.g., forage, grassland fungi, and medicinal herbs). Travel motivation, willingness to pay, tourism expenditure, and overall evaluation.	Data on agricultural products from nine major areas within XG and questionnaire responses from 216 tourists were collected. Survey period: 2 July–2 August 2025.	Material product value and cultural service value accounting	The survey is limited to summer, introducing potential seasonal bias. Recall of 2024 data could introduce memory bias among respondents. Sample coverage lacks sufficient representation in remote pastoral areas.

Third, data formats and measurement units were standardized. While standardizing to a 500 m grid facilitates the spatial alignment of multi-source data and improves processing efficiency, the spatial smoothing effect can lead to a local underestimation of service values from small, fragmented, high-value habitats (e.g., patchy wetlands and riparian zones). A comparative validation based on selected typical riparian and wetland patches (<0.5 km² each) within the study area suggested that this resampling process introduces an overall bias of $\leq 5\%$ to the total regional Gross Ecosystem Product (GEP) estimate. For extensive, homogeneous areas like typical steppe, resampling smooths local heterogeneity but preserves the regional vegetation coverage gradient; consequently, the overall valuation bias for services such as climate regulation and soil conservation remains minimal. To mitigate potential local underestimation, a calibration was performed using field-surveyed distribution data for wetlands and riparian zones, ensuring no systematic bias was introduced in valuing these core functional areas.

Fourth, temporal alignment and verification of temporal consistency with the base year. Using 2024 as the accounting base year, a three-level temporal control mechanism of “data type—temporal matching—backward calibration” was established:

- ① Annual statistical data (e.g., tourist visits) were directly taken from official 2024 statistics.
- ② Multi-year time-series data (e.g., climate, remote sensing) were extracted for the corresponding period in 2024, and temporal scales were harmonized through interpolation and time-series fusion.
- ③ Field survey data (e.g., agricultural/livestock yields, prices, public willingness-to-pay) supplemented regional disparities missing from yearbooks (e.g., price differences for mutton across pastures) and supported zonal valuation calibration.

Because agricultural and pastoral production follows an annual cycle, 2024 output and land-use data were verified retrospectively through field interviews with herders in 2025. Validation showed that price fluctuations for major products ranged within $\pm 3.1\%$ to $\pm 5.2\%$, indicating controllable deviation. Tourism data were considered to have low retrospective risk due to the region’s stable tourism structure and consumption patterns in recent years. The field survey (216 valid samples) focused on local consumption characteristics, further reducing recall bias. It is acknowledged that retrospective surveys can amplify peak-season expenditure estimates and short-term price fluctuation bias. However, by applying a two-way calibration of product prices (using 2024 statistics adjusted with 2025 field data) and scaling total tourist consumption against statistical yearbook figures, the resulting retrospective bias was controlled within 3.5%. This level of bias does not affect the core trends or structural proportions in the GEP accounting, thereby ensuring the authenticity and accuracy of the underlying data.

2.3. Physical Quantity Accounting Methods

The accounting of physical quantities for ecosystem services was based on the selection of biophysical models or statistical formulas guided by three criteria: (1) the representativeness of the service’s underlying ecological process, (2) data availability and quality, and (3) the feasibility of linkage to subsequent monetary valuation methods. This approach ensured both the scientific accuracy of the physical quantification and its direct applicability for economic valuation.

(1) Provisioning Services

The provisioning services of the Xilingol Grassland (XG) primarily include agricultural/forage products and livestock products. The total physical quantity of material products was calculated as:

$$E_{ny} = \sum_{i=1}^n E_i$$

where E_{ny} represents the total output of ecosystem products in $XG(t)$, and E_i denotes the yield of the i -th product category. Data were sourced from field surveys in nine regions and the Xilingol League Statistical Yearbook 2024. In the actual accounting process, full consideration was given to the regional variations in productivity intensity and the management system within XG.

(2) Regulating Service Products

(1) Water Conservation

This study employed the water yield module of the InVEST model for calculation. The InVEST model can integrate multi-source spatial data (precipitation, soil, vegetation), is well-suited for the complex water balance processes in northern arid regions, and outputs physical quantities at the raster scale. This approach both accommodates the spatial heterogeneity of temperate grasslands and provides precise spatialized baseline data for subsequent shadow engineering-based valuation. The fundamental calculation formula is as follows:

$$Y_i = \left(1 - \frac{AET_i}{P_i}\right) \times P_i$$

where Y_i is the annual water yield of raster cell i (mm); AET_i is the annual actual evapotranspiration of raster cell i (mm), calculated using an empirical formula incorporating potential evapotranspiration data, land use, biophysical coefficients (Table 1), and soil data [33]; P_i is the annual precipitation of raster cell i (mm).

$$WR_i = \min\left(1, \frac{Velocity}{249}\right) \times \min\left(1, \frac{0.9 \times TI}{31}\right) \times \min\left(1, \frac{K_{sat}}{300}\right) \times Y_i$$

where WR_i is the water conservation amount of raster cell i (mm); $Velocity$ is the watershed velocity coefficient; TI is the topographic index; K_{sat} is the soil saturated hydraulic conductivity (mm/d).

(2) Soil Retention

The Universal Soil Loss Equation (USLE) is currently the most practical remote sensing-based quantitative model for soil erosion [34]. The InVEST module can integrate it with spatial data to accurately quantify the inhibitory effect of grassland vegetation cover on soil loss. This method aligns with the characteristics of XG's temperate grassland, which experiences both wind and water erosion. The resulting physical quantities can be directly linked to the "sediment dredging + pollution control" valuation logic of the replacement cost method. The calculation formulas are:

$$RKLS = R \cdot K \cdot L \cdot S$$

$$USLE = R \cdot K \cdot LS \cdot C \cdot P$$

$$SD = RKLS - USLE$$

where SD represents the soil retention amount [$t/(hm^2 \cdot a)$]; $RKLS$ represents the potential soil erosion amount [$t/(hm^2 \cdot a)$]; $USLE$ represents the actual soil erosion amount [$t/(hm^2 \cdot a)$]; R denotes the rainfall erosivity factor [$MJ \cdot mm/(hm^2 \cdot h \cdot a)$], derived from precipitation data and relevant empirical formulas; K denotes the soil erodibility factor [$t \cdot hm^2 \cdot h/(hm^2 \cdot MJ \cdot mm)$], calculated using the EPIC model based on soil properties (organic carbon, clay, sand, and silt content) extracted from the Harmonized World Soil Database (HWSD) within the XG boundary; LS denotes the slope length and steepness factor, calculated from DEM data; C and P represent the vegetation cover factor and the soil conservation practice factor, respectively, both of which are dimensionless.

(3) Carbon Sequestration and Oxygen Release

NPP data can be directly obtained from MODIS remote sensing products. This allows for the rapid quantification of grassland vegetation productivity. The carbon–oxygen conversion relationship aligns with the physiological laws of plant photosynthesis. The calculation logic is concise and reproducible. This approach is suitable for the vegetation distribution characteristics of the temperate grassland in XG. It also provides an accurate physical quantity foundation for subsequent monetary valuation using the replacement cost method. Carbon sequestration is an ecological service function where ecosystems absorb atmospheric carbon dioxide through vegetation growth and soil organic matter accumulation. The carbon is then stored long-term in the form of biomass or soil carbon. In this study, NPP was selected for formula calculation.

$$Q_{CO_2} = \sum_{i=1}^n NPP_i \times \frac{M_{CO_2}}{M_C}$$

where Q_{CO_2} is the total mass of CO_2 fixed by ecosystem type i [$g\ CO_2/m^2/a$]; M_{CO_2} is the molecular weight of CO_2 (44); M_C is the atomic weight of carbon (12).

Ecosystem oxygen release is represented by the vegetation net primary productivity (NPP). Since approximately 1 mole of oxygen is released for every 1 mole of carbon fixed, the oxygen provision can be estimated by converting NPP:

$$Q_{O_2} = \sum_{i=1}^n NPP_i \times \frac{M_{O_2}}{M_C}$$

where M_{O_2} is the molecular weight of O_2 (32); M_C is the atomic weight of carbon (12).

(4) Climate Regulation

The climate regulation service was quantified using the formula below. This formula can integrate multi-source data such as vegetation evapotranspiration and ecosystem area. Its calculation logic aligns with the characteristics of climate regulation under drought stress in the XG temperate grassland. The resulting physical quantity (energy consumption) can be directly linked to the “energy substitution” valuation logic of the replacement cost method. The formula is as follows:

$$E_{we} = \sum_{i=1}^n A_i \times ET_i \times q \times 1000/3600$$

where E_{we} is the total energy consumed by ecosystem evapotranspiration ($kW \cdot h/a$); ET_i is the total evapotranspiration within the region; q is the latent heat of vaporization per unit mass of water; A_i is the area of the i -th ecosystem type.

(5) Nutrient Cycling

This study utilized vegetation Net Primary Productivity (NPP) as the fundamental measure of organic matter production. The NPP was converted into dry matter mass using a carbon-to-dry-matter conversion coefficient. This approach effectively bridges remote sensing data with soil sampling data. It is well-suited to the core vegetation–soil nutrient cycling processes in grasslands. The element content coefficients were determined based on local vegetation types. The resulting physical quantity can be accurately connected to the “fertilizer substitution” valuation within the replacement cost method. The calculation formula is as follows:

$$Q_{ne} = \sum_{i=1}^n \left(\frac{NPP_i}{C_i} \cdot f_{ne,i} \cdot A_i \times 10^{-6} \right)$$

where Q_{ne} is the annual retention amount of a specific nutrient element ($t\ N/a$); NPP_i is the net primary productivity of the i -th ecosystem type ($g\ C/m^2/a$); C_i is the proportion of

carbon in organic matter, taken as 0.47; $f_{ne,i}$ is the element content coefficient for the i -th ecosystem type; A_i is the area of the i -th ecosystem type (m^2).

(6) Organic Matter Production

The quantity of organic matter production in this study was calculated based on Net Primary Productivity (NPP). NPP data are rapidly accessible and provide full spatial coverage. The carbon-to-standard-coal conversion coefficient is a universally accepted standard in the field of ecological accounting. Its calculation logic is concise and reproducible. This method is suitable for characterizing the core process of organic matter production in the XG temperate grassland. It also supplies standardized physical quantity data for the subsequent “organic fertilizer substitution” valuation within the replacement cost method. Its calculation formula is as follows:

$$E_{yz} = \sum_{i=1}^n NPP_i \times 1.474$$

where E_{yz} is the organic matter energy value provided by the i -th ecosystem type (g standard coal/ m^2/a), equivalent to the net primary productivity at location i , with 1 g of carbon equivalent to 1.474 g of standard coal.

(3) Cultural Service Products

The physical quantity for cultural services was defined as the number of beneficiaries of the landscape. This includes both the local resident population (357,800) and the annual number of tourist visits to natural landscapes. The annual tourist visit data (3,727,900) were cross-validated using statistical yearbooks and field survey data to correct for potential biases and serve as the primary indicator for evaluating this service.

2.4. Valuation Methods for Monetary Accounting

The monetary accounting of the Gross Ecosystem Product (GEP) for the Xilingol Grassland (XG) was conducted following China’s Technical Guidelines for Gross Ecosystem Product (GEP) Accounting. The general accounting framework is defined as:

$$GEP = EPV + ERV + ECV$$

where GEP refers to Gross Ecosystem Product. EPV denotes Ecosystem Product Value, focusing on core local agricultural and pastoral outputs. ERV stands for Ecosystem Regulating Service Value, highlighting the ecological barrier functions of grasslands. ECV represents Ecosystem Cultural Service Value, which incorporates characteristics of nomadic culture.

The selection of specific valuation and accounting methods follows three principles: service marketability, regional ecological characteristics, and accounting precision requirements.

(1) Valuation Methods for Provisioning Services

The market value method was applied to provisioning services (e.g., agricultural and livestock products). This method aligns with the direct market transaction attributes of these goods and their role as core outputs supporting local livelihoods, ensuring the realism of the valuation. The physical quantities were derived from Section 2.3. Product prices were obtained from field surveys and official sources (local agricultural, forestry, grassland, and statistical departments), reflecting prevailing 2024 market conditions. The value is calculated as:

$$V_m = \sum_{i=1}^n E_i \times P_i$$

where V_m is the value of ecosystem provisioning services (CNY/a); E_i is the yield of the i -th ecosystem product (unit determined by the product, e.g., kg/a); and P_i is the price of the i -th ecosystem product (unit determined by the product, e.g., CNY/kg).

(2) Valuation of Regulating Services

With the exception of scarcity regulation services, the replacement cost method is primarily employed for non-market regulation services, aligning with their characteristics of lacking a direct transaction market while having industrial/agricultural substitution scenarios, in order to quantify their implicit value.

(1) Carbon Sequestration Value

Valued using the replacement cost method, with the regional carbon-trading market price as the core parameter:

$$V_{Cf} = Q_{CO_2} \times C_c$$

where V_{Cf} is the ecosystem carbon sequestration value, Q_{CO_2} is the spatially aggregated annual carbon sequestration amount of the ecosystem (t CO₂/a), and C_c is the carbon price parameter, set at 73.38 CNY/t CO₂ based on the 2023 weighted average carbon allowance price from the Shanghai Environment and Energy Exchange. This value falls within the reference range of carbon-sink pilot projects in Inner Mongolia (e.g., Ordos, Xilingol) and connects with China's "Dual Carbon" goals. The use of a regionally referenced pilot price, rather than a theoretical abatement cost, enhances the practical applicability of the valuation. In this study, the valuation of carbon sequestration and oxygen release is quantified solely based on vegetation Net Primary Productivity (NPP). This reflects the dynamics of carbon absorption and oxygen release through photosynthesis but does not incorporate soil carbon cycle processes such as the accumulation and decomposition of soil carbon pools or soil respiration. Consequently, the results represent only the vegetation-dominated carbon and oxygen fluxes and do not include the contribution of soil carbon dynamics.

Furthermore, the weighted-average annual carbon price adopted in this study, while smoothing short-term fluctuations, does not fully capture long-term trend variations. Influenced by national carbon-market policies such as sector expansion and increased CCER supply, the Shanghai carbon price exhibits significant multi-year trend fluctuations. The local carbon market in Inner Mongolia remains in a pilot phase, with trading volumes substantially lower than those of the Shanghai market. Although the Shanghai carbon price overlaps with local reference prices, it essentially reflects cross-regional market pricing and thus fails to fully capture the "local specificities" of grassland carbon-sink projects in Inner Mongolia—such as regional restoration costs and the added value of ecological protection—resulting in a degree of price-transmission lag. Moreover, the Shanghai market primarily covers industrial emission allowances and forestry carbon sinks, while grassland carbon sinks differ from forestry sinks in aspects such as vegetation-carbon stability and monitoring challenges (e.g., small-patch heterogeneity). The prevailing carbon price does not adequately reflect the regional characteristics of grassland carbon sinks, including their high long-term maintenance costs and the complexity of additionality demonstration, representing to some extent a limitation in "applying a generic price to value a spatially and ecologically distinct asset."

(2) Oxygen Release Value

The replacement cost method was used, benchmarked against industrial oxygen production costs, which suits the quasi-public good nature of oxygen. The accounting formula is:

$$V_{Op} = Q_{O_2} \times C_c$$

where V_{Op} is the oxygen release value; Q_{O_2} is the annual oxygen release (calculated based on vegetation productivity and photosynthetic mechanism models); and C_c is the industrial oxygen production price, taken as 445 CNY/t (the regional average cost of industrial oxygen production), ensuring regional adaptability.

(3) Climate Regulation Value

The replacement cost method was applied, focusing on the “cooling effect” of grassland evapotranspiration (a core regional ecological function), using the cost savings in energy as the valuation basis. The accounting formula is:

$$V_{tt} = E_{tt} \times P_e$$

where V_{tt} is the climate regulation value (CNY/a); E_{tt} is the equivalent energy saved by evapotranspiration (kW·h/a); and P_e is the local electricity price, taken as 0.5 CNY/kW·h (the publicly available average on-grid tariff in the region where XG is located). The cooling effect of grassland climate regulation is considered equivalent to substituting for industrial/domestic cooling electricity consumption. This electricity price reflects the average cost of thermal and renewable power generation, allowing for a reasonable quantification of the saved energy value.

(4) Water Conservation Value

The shadow project method was used, adapted to the regional characteristic of water scarcity in northern arid and semi-arid China, quantifying its ecological value based on the cost of equivalent reservoir construction. The accounting formula is:

$$V_{wr} = WR \times C_{we}$$

where V_{wr} is the water conservation value; WR is the total annual water conservation (calculated by coupling water balance and evapotranspiration models); and C_{we} is the shadow price per unit of water, set at 1.8 CNY/m³ (the publicly announced 2023 regional benchmark price for water rights transactions in Inner Mongolia). XG belongs to a northern arid/semi-arid region with a multi-year average precipitation of only 234 mm, indicating significant water scarcity. This price aligns with local water supply and demand realities.

(5) Soil Conservation Value

The replacement cost method was applied, addressing regional issues of low soil organic matter content (approx. 20.9 g/kg) and high desertification risk in grasslands. Valuation was divided into two parts: “reduction in sediment deposition” and “reduction in non-point source pollution.” The accounting formulas are:

$$V_{sr} = V_{sd} + V_{dpd}$$

$$V_{sd} = \lambda \times (Q_{sr}/\rho) \times c$$

$$V_{dpd} = \sum_{i=1}^n Q_{sr} \times C_i \times P_i$$

where V_{sr} is the total soil conservation value; V_{sd} is the value from reduced sediment deposition; V_{dpd} is the value from reduced non-point source pollution; Q_{sr} is the annual soil conservation amount (modified based on the soil loss equation and grassland vegetation cover characteristics); λ is the sediment deposition coefficient; ρ is the soil bulk density; c is the unit cost of sediment dredging; C_i is the nutrient content; and P_i is the corresponding treatment cost (aligning with the characteristic that grassland non-point source pollution is primarily nitrogen and phosphorus).

(6) Nutrient Cycling and Organic Matter Production Values

Both used the replacement cost method, adapted to the core need for maintaining soil fertility in grasslands, quantifying their implicit value based on market prices for chemical or organic fertilizers.

① Nutrient Cycling Value:

$$V_y = \sum_{i=1}^n Q_{ne} \times P_i$$

where V_y is the nutrient cycling value; Q_{ne} is the annual return amount of the i -th nutrient element; and P_i is the corresponding chemical fertilizer market price, set at 2000 CNY/t (the 2024 average wholesale price of urea in the Inner Mongolia agricultural materials market). As urea is the most commonly used nitrogen fertilizer in the region (with a pure nitrogen content of 46%), this translates to a unit value of 4348 CNY/t of pure nitrogen, consistent with the actual purchase price for herders.

② Organic Matter Production Value:

$$V_{yz} = E_{yz} \times P_i$$

where V_{yz} is the organic matter production value; E_{yz} is the annual organic matter input (accounting for processes like vegetation litter decomposition and root exudation); and P_i is the organic fertilizer market price in the Inner Mongolia Autonomous Region, taken as 300 CNY/t (the average price for regional compost and humic acid fertilizers). This price reflects the realities of organic fertilizer production and sales in pastoral areas, excluding long-distance transportation costs, fitting the logic of localized accounting.

(3) Valuation of Cultural Services

In line with the regional characteristics of XG, which integrates “landscape aesthetics and ecotourism,” and considering the non-market nature and well-being-oriented essence of cultural services, this study employed the contingent valuation method (CVM) to value landscape aesthetic services and the travel-cost method (TCM) to assess ecotourism value. This approach enhances the comprehensiveness and regional relevance of the accounting results.

Landscape Value: The contingent valuation method (willingness-to-pay method) was applied. The valuation quantified the aesthetic value derived from the region’s unique landforms and integrated folk culture, using the number of residents and tourists benefiting from the landscape services and a defined proportion of annual income as key parameters. The accounting formula is:

$$A = \sum_{i=1}^n N_i \times P_i$$

where A is the total landscape aesthetic value; N_i denotes the population size of beneficiary group i (e.g., local residents and non-local tourists); and P_i represents the average per capita willingness to pay for that group (for detailed data characteristics, see Section 2.2, Field Survey Data).

Ecotourism Value: The travel-cost method was used, considering the “ecology-dependent” nature of regional ecotourism. The valuation was conducted by coupling total tourism revenue with the proportion attributable to ecological contribution. The accounting formula is:

$$N = \sum_{i=1}^n N_i$$

where N denotes the total annual number of tourist visits and N_i represents the number of visitors to ecosystem i , the per capita tourism expenditure was derived from field survey data (for detailed statistical characteristics, refer to Section 2.2, Field Survey Data).

3. Results

3.1. Structure and Overall Characteristics of Gross Ecosystem Product

Based on the comprehensive accounting of ecosystem value within the GEP framework, the annual Gross Ecosystem Product (GEP) of XG is estimated at CNY 170.5229 billion (Table 2). Of this total, regulating services contribute CNY 166.726 billion, accounting for

97.77% of GEP; provisioning services amount to CNY 1.706 billion (1.00%); and cultural services reach CNY 2.091 billion (1.23%).

Table 2. Summary of Monetary Values from Ecological Product Accounting for XG.

Category	Accounting Item	Accounting Method	Physical Quantity	Monetary Value (CNY Billion)
Provisioning services (CNY 17.06 billion)	Agricultural Products	Market Value Method	2.90 (10 ⁴ tonnes)	2.897
	Livestock Products	Market Value Method	6.51 (10 ⁴ tonnes)	14.162
Regulating Service Products (CNY 1667.26 billion)	Carbon Sequestration	Replacement Cost Method	5.57 (10 ⁶ t CO ₂ -eq)	4.09
	Oxygen Release	Market Value Method	4.05 (10 ⁶ t)	22.11
	Climate Regulation	Replacement Cost Method	32.03 (10 ¹¹ kW·h)	1601.5
	Water Conservation	Shadow Project Method	42.78 (10 ⁷ m ³)	7.7
	Soil Retention	Replacement Cost Method	5.95 (10 ⁸ t)	18.27
	Nutrient Cycling	Replacement Cost Method	1.58 (10 ⁵ t N)	6.87
	Organic Matter Production	Replacement Cost Method	2.24 (10 ⁶ t)	6.72
Cultural Service Products (CNY 20.91 billion)	Ecotourism	Travel Expense Method	—	6.1
	Landscape	Willingness to pay method	—	14.81
Total GEP				1705.229

A comparative analysis across service types reveals that regulating services constitute the unequivocally dominant component of GEP. Their total value substantially surpasses the combined sum of provisioning and cultural services (CNY 3.8 billion). Within the regulating services category, the value distribution is highly skewed. Climate regulation alone accounts for CNY 160.15 billion, representing 95.93% of the total value of regulating services. In contrast, the combined contribution of the remaining five regulating services—including carbon sequestration (CNY 0.409 billion) and organic matter production (CNY 0.672 billion)—amounts to merely 4.07%. Within cultural services, the landscape aesthetic value (CNY 1.481 billion) represents 70.8% of the total cultural service value. In cross-type comparisons, the value of regulating services is 97.7 times that of provisioning services and 79.7 times that of cultural services. It is important to note, however, that the pronounced dominance of climate regulation value stems primarily from the methodological adaptation in this study, which specifically targets the “climate regulation as a core ecological barrier function” of the XG temperate grassland. This result therefore reflects a valuation focus rather than a definitive ranking of the ecosystem’s intrinsic service weights.

3.2. Valuation of Regulating Services

This section quantifies six key regulating services: carbon sequestration and oxygen release, climate regulation, water conservation, soil conservation, nutrient cycling, and organic matter production. For each service, the value, spatial characteristics, and relevant contextual information (e.g., sensitivity and uncertainty) are presented below, supported by spatial distribution maps and global Moran’s I analysis.

(1) Carbon Sequestration and Oxygen Release Value

The annual carbon sequestration in XG was equivalent to the absorption of 5.57×10^6 t CO₂. Based on the 2023 regional average carbon trading price of 73.38 CNY/t (Shanghai Environment and Energy Exchange), the carbon sequestration value was CNY 0.409 billion. Annual oxygen release reached 4.05×10^6 t O₂. Using the regional average industrial oxygen production cost of 445 CNY/t as a proxy, the oxygen release value was estimated at CNY 1.802 billion. The combined value of these two services totaled CNY 2.211 billion.

To verify the robustness of the carbon sequestration estimate, a cross-validation was performed using the benefit-transfer method. With reference to the carbon-sink

benefit-transfer coefficient for semi-arid temperate grasslands (1.2–1.5 USD/t CO₂) reported in the Global Assessment Report on Grassland Ecosystem Services [20], and considering the stable carbon-sink supply of the Xilingol grassland (annual NPP fluctuation coefficient < 8%), the transferred carbon-sink value ranged from CNY 0.398 to 0.491 billion. This range closely aligns with the primary-method result of CNY 0.409 billion, showing a deviation of only 2.7%—well within the acceptable margin of error for ecological accounting—thus supporting the reliability of the estimate.

Spatial distribution maps (Figures 4 and 5) show that high values for carbon sequestration and oxygen release were concentrated in the core protected zones of XG with high vegetation cover and in the southeastern meadow-steppe regions. This distribution exhibited a spatial trend visually comparable to that of NPP, with overlapping high-value areas covering approximately 68% of the core protected zone.

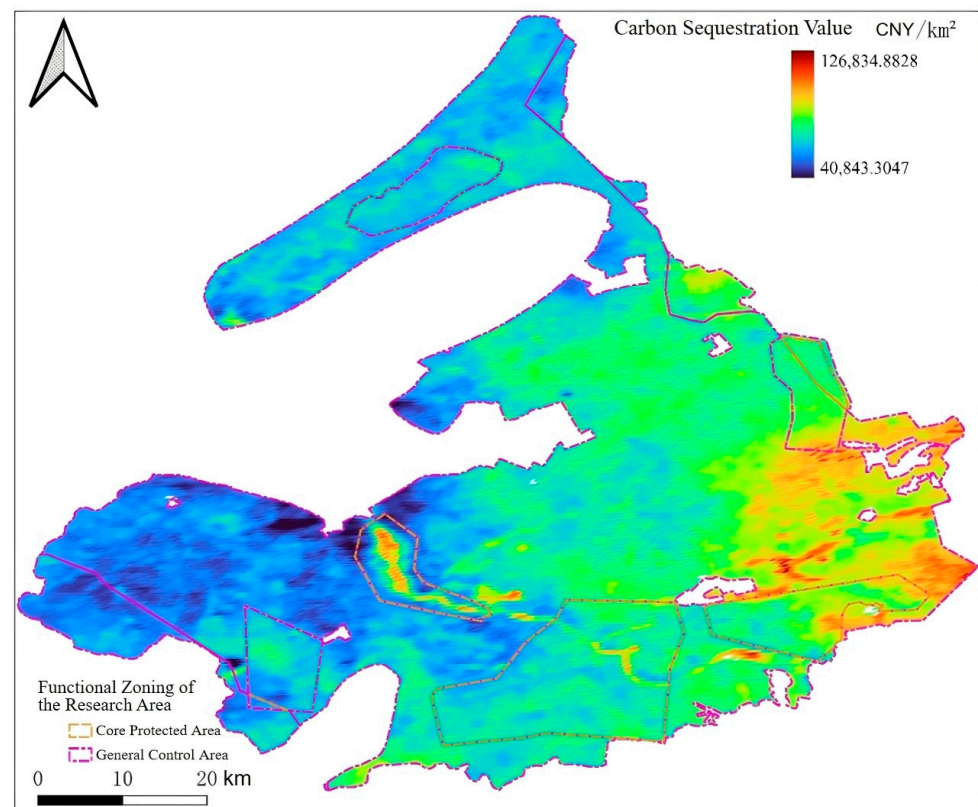


Figure 4. Spatial Distribution Map of Carbon Sequestration Value in XG.

Global Moran's I analysis revealed significant spatial autocorrelation for both services: the Moran's I value was 0.48 ($p < 0.01$, Z-score = 3.12) for carbon sequestration value and 0.46 ($p < 0.01$, Z-score = 2.97) for oxygen release value, indicating a clear high-high and low-low clustering pattern. Furthermore, spatial correlation analysis confirmed strong positive relationships between these service values and NPP, with Pearson correlation coefficients of 0.79 (carbon sequestration) and 0.76 (oxygen release) ($p < 0.01$), quantitatively affirming the dominant role of vegetation productivity in shaping their spatial patterns.

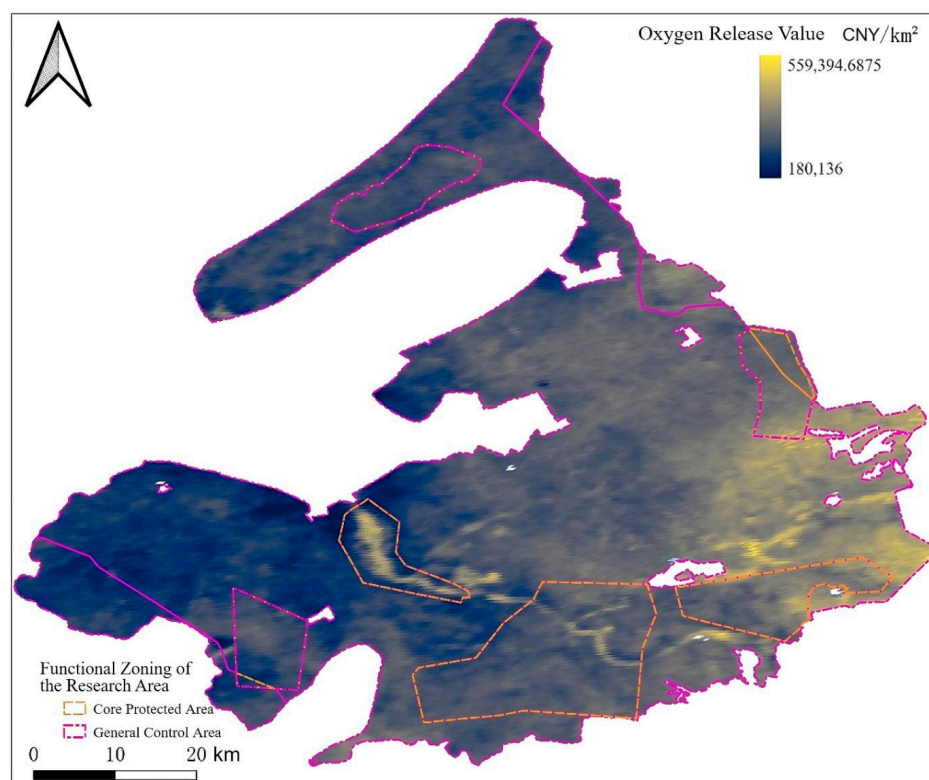


Figure 5. Spatial Distribution Map of Oxygen Release Value in XG.

(2) Climate Regulation Value

The core grassland area of XG was calculated to be 1.97×10^7 ha. Using a unit value of $8129 \text{ CNY ha}^{-1} \text{ yr}^{-1}$, the total climate regulation value reached CNY 160.15 billion (Figure 6), constituting 93.9% of the total GEP.

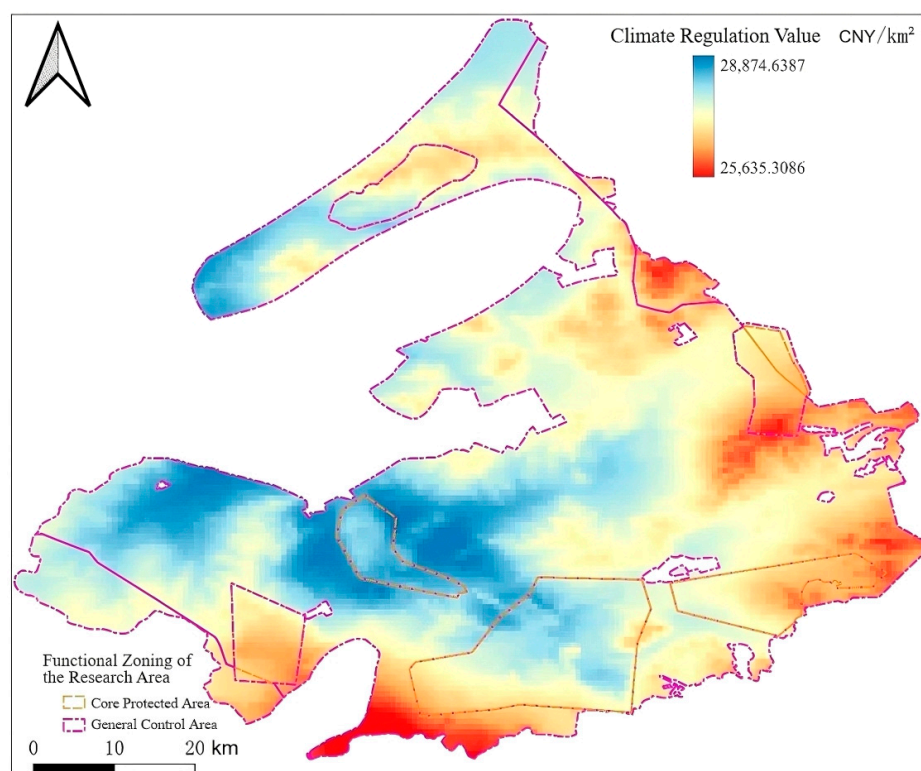


Figure 6. Spatial Distribution Map of Climate Regulation Value in XG.

This notably high proportion is consistent with findings from prior GEP and ecosystem service valuation studies in northern grasslands and Inner Mongolia, where regulating services (including climate regulation) are consistently identified as the dominant component of grassland ecological value [35,36]. For instance, the 2023 GEP accounting for Hulunbuir City reported that regulating services constituted 89.9% of the total GEP [35], and a comprehensive assessment of China's grassland ecosystems estimated that ecological regulation functions contribute 84% of the total value [36]. Moreover, in arid and semi-arid regions of northern China, such as Inner Mongolia and Tibet, the proportion of regulating services (e.g., climate regulation and windbreak and sand fixation) tends to be significantly higher than the national average, reflecting their critical role as ecological barriers [37].

To clarify the validity and limitations of this high proportion, we conducted two counterfactual comparisons based on the sensitivity analysis results in Table 3. First, lowering the benchmark electricity price from 0.5 CNY kW·h^{−1} to 0.4 CNY kW·h^{−1} (a −20% change) reduced the GEP by −3.6% and lowered the share of climate regulation value to 77.9%. Second, drawing on empirical studies of grassland ecosystem services in northern China [37] and considering XG's role as a northern ecological security barrier, we applied a 50% local direct-benefit accounting ratio (including only local direct benefits and excluding cross-regional indirect benefits). This adjustment further reduced the proportion to 76.3%. These results indicate that, even under different valuation boundaries, climate regulation remains the dominant component of GEP—its share still far exceeds the combined total of provisioning and cultural services (2.23%)—and all value differences remain within the overall uncertainty range of ±9.3%.

Table 3. Summary of Sensitivity Analysis Results.

Parameter Type	Fluctuation Range	Reference Value	Parameter Values After Changes	GEP Total Value (CNY Billion)	GEP Change Rate (%)	Sensitivity Coefficient
Regional carbon trading price	+20%	73.38 CNY/t CO ₂	88.056 CNY/t CO ₂	1814.363	+6.4	0.32
	+10%		80.718 CNY/t CO ₂	1759.796	+3.2	
	−10%		66.042 CNY/t CO ₂	1650.662	−3.2	
	−20%		58.704 CNY/t CO ₂	1596.095	−6.4	
Industrial oxygen production cost	+20%	445 CNY/t O ₂	534 CNY/t O ₂	1795.173	+5.4	0.27
	+10%		489.5 CNY/t O ₂	1750.201	+2.7	
	−10%		400.5 CNY/t O ₂	1615.285	−2.7	
	−20%		356 CNY/t O ₂	1660.257	−5.4	
Net Primary Productivity (NPP)	+20%	259.77 g C/m ²	311.72 g C/m ²	1773.44	+3.9	0.24
	+10%		285.75 g C/m ²	1739.33	+2.0	
	−10%		233.79 g C/m ²	1671.13	−2.0	
	−20%		207.82 g C/m ²	1637.03	−3.9	
Water resource trading price	+20%	1.8 CNY/m ³	2.16 CNY/m ³	1778.159	+4.2	0.21
	+10%		1.98 CNY/m ³	1741.694	+2.1	
	−10%		1.62 CNY/m ³	1668.764	−2.1	
	−20%		1.44 CNY/m ³	1632.299	−4.2	
Average electricity price	+20%	0.5 CNY/kW·h	0.6 CNY/kW·h	1766.636	+3.6	0.18
	+10%		0.55 CNY/kW·h	1735.932	+1.8	
	−10%		0.45 CNY/kW·h	1674.526	−1.8	
	−20%		0.4 CNY/kW·h	1643.822	−3.6	
Urea trading price	+20%	2000 CNY/t	2400 CNY/t	1756.368	+3.0	0.15
	+10%		2200 CNY/t	1730.798	+1.5	
	−10%		1800 CNY/t	1679.660	−1.5	
	−20%		1600 CNY/t	1654.090	−3.0	

Table 3. Cont.

Parameter Type	Fluctuation Range	Reference Value	Parameter Values After Changes	GEP Total Value (CNY Billion)	GEP Change Rate (%)	Sensitivity Coefficient
Average organic fertilizer trading price	+20%	300 CNY/t	360 CNY/t	1735.777	+1.8	0.09
	+10%		330 CNY/t	1720.503	+0.9	
	−10%		270 CNY/t	1689.955	−0.9	
	−20%		240 CNY/t	1674.681	−1.8	
Carbon-to-dry-matter conversion coefficient	+20%	0.47	0.564	1720.69	+0.91%	0.09
	+10%		0.517	1715.54	+0.48%	
	−10%		0.423	1695.08	−0.48%	
	−20%		0.376	1689.93	−0.91%	
Carbon-to-standard coal conversion coefficient	+20%	1.474	1.769	1718.40	+0.77%	0.08
	+10%		1.621	1711.39	+0.36%	
	−10%		1.327	1699.25	−0.36%	
	−20%		1.179	1692.23	−0.77%	

Figure 6 shows that areas of high climate-regulation value are concentrated in the central-southern part of the study area with continuous vegetation cover, whereas low-value areas cluster in the northwestern sandy lands and sparse-vegetation zones, exhibiting clear spatial consistency with the regional vegetation-coverage gradient. Global Moran's I analysis yielded a value of 0.53 ($p < 0.01$, Z-score = 3.35), indicating the most pronounced spatial agglomeration among all services analyzed. High-value clusters show a strong spatial correspondence with the central-southern continuous-vegetation areas, while low-value clusters align closely with the northwestern sandy and sparse-vegetation zones. This quantitatively confirms the core characteristic that the spatial pattern of climate-regulation value is dominated by the vegetation-coverage gradient.

(3) Water Conservation Value

The annual water conservation volume in XG was $42.78 \times 10^7 \text{ m}^3$. Valued at the 2023 Inner Mongolia water resource trading price of 1.8 CNY m^{-3} , the total water conservation value amounted to CNY 0.77 billion. Spatially, the water conservation value exhibited a decreasing gradient from the southeast to the northwest (Figure 7), corresponding closely to the regional precipitation distribution. High-value areas were concentrated in the southeastern wetlands and meadow-steppe regions, covering approximately 23% of the total study area. Global Moran's I analysis yielded a value of 0.39 ($p < 0.01$, Z-score = 2.61), indicating statistically significant spatial clustering. High-value clusters showed a clear spatial correspondence with the southeastern wetlands and high-precipitation zones, whereas low-value clusters aligned with the arid sandy lands in the northwest. This distribution pattern aligns with the regional hydrothermal resource gradient, further supporting the robustness of the observed spatial pattern.

(4) Soil Conservation Value

Given the low soil organic matter content (approximately 20.9 g/kg) in the typical Kastanozems and the significant desertification risk in the study region (XG), the replacement cost method was applied. The total soil conservation value, calculated as the sum of the values for reduced sediment siltation and reduced non-point source pollution, was estimated at CNY 1.827 billion annually. Based on the Revised Universal Soil Loss Equation (RUSLE) model and multi-source data, the annual soil retention volume reached $5.95 \times 10^8 \text{ t}$. The corresponding economic value was calculated as CNY 0.0357 billion for reduced sediment siltation and CNY 0.14381 billion for reduced non-point source pollution.

To verify the robustness of this result, a comparison was made using the protective expenditure method. Using the actual management cost of 320 CNY/mu from Inner Mongolia's Grassland Ecological Protection Subsidy and Reward Policy (for "fencing enclosure + light reseeding") as the input parameter, the derived soil conservation

value was CNY 1.720 billion. The difference of only 5.8% between the two methods falls within the acceptable error range for ecological accounting, confirming the absence of systematic overestimation.

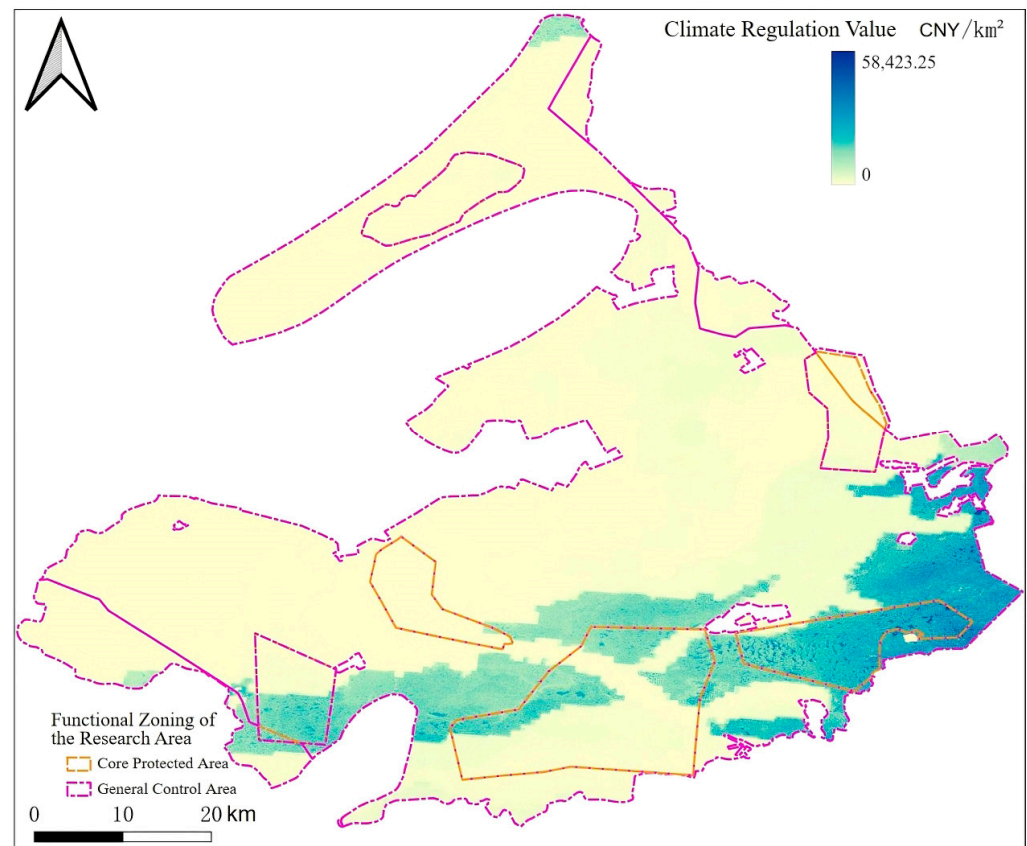


Figure 7. Spatial Distribution Map of Water Conservation Value in XG.

Spatial analysis integrating remote sensing and GIS techniques reveals significant spatial differentiation in soil conservation value (Figure 8). Values in areas such as Maodeng Ranch and Baiyinxile Ranch show a fluctuating upward trend, while some typical steppe areas face higher erosion risks. In these vulnerable zones, inadequate protection could lead to a 10–20% decline in their ecological service value. This observed spatial variation was derived from a comparative analysis of zonal accounting data. A global Moran's I analysis indicates a Moran's I value for soil conservation of 0.42 ($p < 0.01$, Z-score = 2.78). Significant high-value clusters are concentrated around the core protected areas with high vegetation cover and in low-erosion-risk zones. Conversely, low-value clusters correspond well with the sandy lands and high-erosion-risk areas in the northwest spatially. This finding quantitatively confirms the spatial heterogeneity of regional soil conservation values, which is consistent with the distribution pattern shown in Figure 8.

(5) Nutrient Cycling Value

The annual value of nutrient cycling was estimated at CNY 0.687 billion using the replacement cost method, referenced to local fertilizer prices and integrated with MODIS NPP data and field-measured soil nutrient information. In terms of physical quantity, XG sequestered 15.8×10^4 t of pure nitrogen in 2023. Based on the local urea market price in Inner Mongolia (approximately 2000 CNY/t, with a pure nitrogen content of 46%), the effective unit value equates to 4348 CNY per tonne of pure nitrogen, which forms the basis for the monetary valuation.

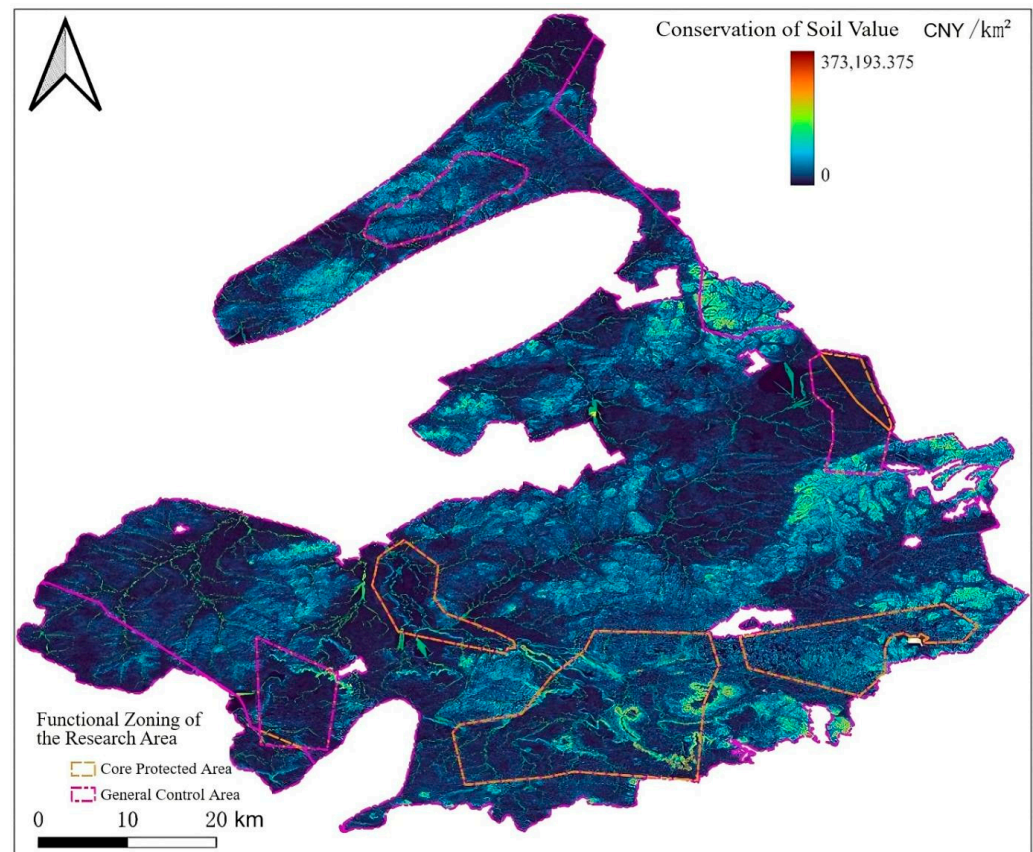


Figure 8. Spatial Distribution Map of Soil Conservation Value in XG.

(6) Organic Matter Production Value

Given the relatively low soil organic matter content in XG, the organic fertilizer replacement cost method was applied, supported by multi-source data including vegetation litter monitoring, soil sampling, and microbial activity measurements. This yielded an annual value of CNY 0.672 billion. The annual organic matter production in XG for 2023 reached 224×10^4 t, which was monetized using the local average organic fertilizer price in Inner Mongolia of 300 CNY/t.

3.3. Valuation of Provisioning Services and Cultural Services

(1) Material Product Value

The accounting results indicate a total agricultural output value of CNY 0.290 billion for the reserve, stemming from the production of 29,000 tons of agricultural and forage products (e.g., forage grass, potatoes, and wheat). The total animal husbandry output value is CNY 1.416 billion, associated with the production of 65,100 tons of livestock products (e.g., beef, mutton, and milk). Consequently, the total value of provisioning services amounts to CNY 1.706 billion.

(2) Cultural Services Value

The total value of cultural services is CNY 2.091 billion. Based on data from the Xilingol League Statistical Yearbook 2024 and an analysis of public willingness-to-pay derived from field surveys, the landscape value for 2024 was estimated at CNY 1.481 billion. Furthermore, by integrating the annual total tourist visits and tourism revenue from the aforementioned statistical yearbook with tourist consumption data from field surveys, the ecotourism value for 2024 was calculated at CNY 0.610 billion.

3.4. Sensitivity and Uncertainty Analysis

This analysis focuses on quantifying parameter responses and errors at a numerical level and does not extend to a quantitative statistical analysis of spatial distributions. A sensitivity analysis was conducted to assess the impact of fluctuations in core parameters on the GEP results. This was combined with an uncertainty analysis to identify dominant error sources. This integrated approach strengthens the linkage between the analytical outcomes and the core dimensions of the 3M framework, thereby supporting its overall rationality.

(1) Sensitivity Analysis

A one-factor-at-a-time method was employed. Given that regulating services constitute 97.77% of the total GEP, two categories of core parameters were selected for evaluation. Price parameters relevant to regional applicability (detailed in Section 2.4): the regional carbon trading price (73.38 CNY/t CO₂), industrial oxygen production cost (445 CNY/t O₂), average electricity price (0.5 CNY/kWh), water resource trading price (1.8 CNY/m³), urea trading price (2000 CNY/t), and the average organic fertilizer trading price (300 CNY/t). Key parameters and standardized coefficients for the physical quantity accounting of regulating services: the Grassland Net Primary Productivity (NPP)—serving as the foundational input for services including carbon sequestration & oxygen release and organic matter production, the carbon-to-dry-matter conversion coefficient (0.47), and the carbon-to-standard-coal conversion coefficient (1.474). With reference to conventional fluctuation ranges in ecological value accounting [18], variation amplitudes of ±10% and ±20% were set. The influence intensity was then ranked using sensitivity coefficients and the GEP change rate.

Sensitivity Coefficient:

$$S = (\Delta V / V_0) / (\Delta P / P_0)$$

where V is the baseline GEP value (CNY 170.5229 billion), ΔV is the change in GEP after parameter variation; P_0 is the baseline parameter value, and ΔP is the parameter variation amount.

GEP Change Rate:

$$\text{Change Rate} = [(V - V_0) / V_0] \times 100\%$$

As shown in the Table 3, the sensitivity coefficients of the key parameters are ranked as follows: regional carbon trading price (0.32) > industrial oxygen production cost (0.27) > NPP (0.24) > regional water resource trading price (0.21) > average electricity price (0.18) > urea wholesale price (0.15) > average organic fertilizer price (0.09) = carbon-to-dry-matter conversion coefficient (0.09) > carbon-to-standard-coal conversion coefficient (0.08). This ranking aligns with the proportional contribution of different regulating services to the total GEP. Specifically, parameters linked to core ecological barrier functions—carbon sequestration and oxygen release—exert a substantially greater influence on the total GEP than those associated with soil-fertility maintenance (i.e., nutrient cycling and organic matter production). As the fundamental input for three core regulating services (carbon sequestration, oxygen release, and organic matter production), NPP affects multiple service values and consequently ranks third (sensitivity coefficient = 0.24). The two key empirical coefficients (carbon-to-dry-matter and carbon-to-standard-coal) show high stability, being based on widely accepted industry standards and local validation; their sensitivity is therefore low and does not alter the dominance of the core price and biophysical parameters. Under a ±20% variation in individual parameters, the maximum induced GEP change rate is ±6.4% (attributable to fluctuation in the regional carbon trading price). Biophysical conversion coefficients have a negligible effect on the overall variance. When considering the combined effect of simultaneous variations in multiple core parameters within a

practical accounting scenario, the maximum total GEP change rate reaches $\pm 8.7\%$. Both values remain below the 10% threshold commonly accepted in ecological accounting [18].

(2) Uncertainty Analysis

This study employs a Monte Carlo simulation combined with an error decomposition method for uncertainty analysis. Prior to determining the optimal number of iterations, stability was verified through a convergence test: starting from 500 iterations and gradually increasing the count, the fluctuation in the calculated uncertainty error fell below 0.3% when the number of iterations reached 800. By 1000 iterations, the error results stabilized effectively, with negligible fluctuations, meeting the convergence requirements for ecological accounting. Further increasing the iteration count did not lead to any substantial difference in the error values. Thus, this study ultimately set 1000 as the optimal number of iterations for the Monte Carlo simulation.

This analysis quantifies and discusses three principal sources of uncertainty. The analysis specifically addressed three distinct error sources. The data-resolution error (U_1) originates from precision inconsistencies during multi-source data integration. This includes the inability of 500 m MODIS NPP data to resolve fine-grained heterogeneity in small-patch wetlands and sparse forests on sandy land; classification ambiguities between sparse grassland and sandy land within the 30 m CLCD land-use dataset; local biases in precipitation estimates derived from 1 km interpolated climate data; and resolution mismatches between soil data and other spatial datasets (Table 1). The method-selection error (U_2) arises from the inherent bias of the “differentiated method adaptation” strategy employed—for instance, valuing regulating services via the replacement cost method while applying the market value method to provisioning services. The core of this bias lies in the conceptual discrepancy between the industrial-substitution premise of methods like replacement cost and shadow project pricing, and the fundamental characteristics of grassland ecosystem services as public goods requiring long-term ecological sustainability. The parameter-uncertainty error (U_3) stems from the inherent variability of regionalized parameters. This encompasses seasonal fluctuations in market-based parameters (e.g., carbon price, electricity tariff, water-rights trading price), spatial heterogeneity in biophysical parameters such as NPP, and potential biases introduced by seasonal field survey constraints, respondent recall bias in questionnaires, and non-centralized livestock product data in statistical yearbooks (Table 1). Using the GEP of XG (CNY 170.5229 billion) as the baseline, the total composite error was quantified through the variance-synthesis method, a standard approach in ecological accounting [18]. The formula is as follows:

$$\text{Total Uncertainty Error : } U_{total} = \sqrt{U_1^2 + U_2^2 + U_3^2}$$

The results demonstrate that by implementing optimization strategies—such as coupling and calibrating remote sensing data with in situ sampling points, supplementing with field survey data (including agricultural and livestock product yields, tourist willingness-to-pay, etc.), and conducting cross-validation across multiple data sources—the potential error from multi-source data integration in this study was reduced to $U_1 = 6.5\%$. This result implies that future ecological management should enhance high-resolution monitoring to support more refined decision-making, especially for the targeted protection of key ecological patches.

The inherent bias arising from the “differentiated method adaptation” framework—for instance, the discrepancy between the industrial-substitution assumption of the replacement cost method and the public-good nature of grassland ecosystem services—resulted in a method-selection error of $U_2 = 5.0\%$. Employing multi-method cross-validation (e.g., comparing the replacement cost method with the protective-expenditure method for soil

conservation, or validating carbon-sequestration values using the benefit-transfer method) can mitigate such bias. The error remains within a controllable range, and this outcome provides methodological support for “cross-verification through multiple methods” in policy formulation, potentially reducing decision-making risks associated with reliance on a single accounting approach. The parameter-uncertainty error reached $U_3 = 4.3\%$, caused by actual fluctuations in regionalized parameters, such as seasonal market variations, spatial heterogeneity of biophysical parameters, and sampling bias in field surveys. Using local annual-average market data and multi-regional cross-validation (e.g., aligning carbon prices with the trading range of Inner Mongolia’s pilot markets) can help attenuate this bias. This error reflects the necessity of dynamically updating regionalized parameters and indicates a direction for optimizing the dynamic management of ecological assets.

After synthesis, the total uncertainty of this study is $\pm 9.3\%$. Based on a 95% confidence interval, the GEP of the study area ranges between CNY 154.73 billion and CNY 186.31 billion, demonstrating good robustness. This reasonably bounded, low-error result provides credible data support for the implementation of policies related to XG’s ecological-asset accounting, carbon-sink trading, and cross-regional ecological compensation. Furthermore, the spatial heterogeneity of the errors supplies a basis for spatially differentiated policy. The core protected area could establish long-term, fixed ecological-compensation standards based on its stable valuation results, while the general control area requires a dynamic adjustment mechanism, with valuation updates every 3–5 years to balance conservation and development needs.

4. Discussion

The 3M GEP accounting framework proposed in this study represents not a disruptive breakthrough but a targeted refinement of established accounting guidelines, focusing on three key dimensions: indicator selection, method application, and data validation. This refinement is explicitly tailored to the specific ecological and institutional context of XG as a National Nature Reserve and a representative temperate grassland ecosystem. The core contribution lies in the localized adaptation of prior GEP methodologies to XG’s actual conditions. This adaptation entailed: focusing indicators on regionally salient ecological functions while excluding incompatible items; selecting and cross-validating valuation methods based on the attributes of local ecological products; and strengthening credibility through multi-source data verification. Collectively, these modifications enhance the capacity of a general GEP framework to reflect site-specific ecological characteristics and to support the practical management of diverse types of natural protected areas.

4.1. Indicator Selection: Optimizing for Adaptation to Regional Characteristics

The indicator system was optimized according to a principle of removing mismatched items, reinforcing core functions, and adding regionally distinctive elements. In contrast to more generic frameworks, provisioning-service indicators were limited to core agricultural (e.g., potato, wheat, forage grass) and livestock outputs (e.g., cattle, sheep, meat, milk), excluding scarce forestry and fishery products. This adjustment reflects XG’s actual resource profile and is consistent with the view that temperate grassland accounting requires strong regional parameter adaptation [38]. For regulating services, the set prioritizes four key functions: carbon sequestration and oxygen release, climate regulation, soil conservation, and water conservation. This emphasis aligns with the strategic role of temperate grasslands as the “Northern Ecological Security Barrier” and addresses region-specific pressures such as pronounced drought stress and high wind-erosion risk. It echoes core indicators from northern grassland studies [37] and follows the IPBES recommendation for arid grasslands to focus on essential regulating functions like windbreak, sand fixation, and

water conservation [20]. By prioritizing indicators functionally, this approach mitigates the common shortcoming of “indicator homogenization,” which often obscures region-specific ecological contributions. Cultural-service indicators were expanded to include the landscape value of “grassland + Mongolian nomadic culture,” refining the conventional focus on ecotourism and scientific education. This addition acknowledges the human–ecological coupling characteristic of temperate grasslands [39] and resonates with the TEEB principle that cultural services should integrate region-specific socio-ecological elements [40], thereby enabling a more comprehensive reflection of local integrated value.

The rationale for this selection is further corroborated by sensitivity-analysis results. Parameters associated with core ecological-barrier functions—such as the carbon-trading price, industrial oxygen-production cost, and grassland Net Primary Productivity (NPP)—exerted the strongest influence on total GEP, confirming that the selected indicators reflect XG’s strategic role as an ecological security barrier. In contrast, parameters related to soil-fertility maintenance (e.g., urea and organic-fertilizer prices) showed lower sensitivity, aligning with their objectively smaller contribution to total GEP. Together, these findings reinforce the targeted design and internal consistency of the indicator system.

Finally, the study eschews generic parameter values in favor of locally sourced market data. Although this may introduce parameter uncertainty ($U_3 = 4.3\%$) due to sampling bias or seasonal variation, it is more representative of actual local conditions and better suited to XG’s accounting needs. As noted in comparable studies, regionally calibrated adjustments—even with minor deviations—generally improve the practical relevance of accounting results for local conservation [41].

4.2. Method Application: Differentiated Adaptation to Product Attributes and Regional Context

This study applies established ecological valuation methods, with its main innovation being the bidirectional adaptation to local product attributes and regional characteristics through locally derived parameters. Provisioning services, given their marketability, were valued using the market value method—a common practice for grasslands [9]. For non-market regulating services, the replacement cost method was applied, while the shadow-project method was used specifically for water conservation. Cultural services were valued by combining the contingent-valuation and travel-cost methods. This differentiated yet integrated methodological logic follows the general paradigm for valuing ecological products [18] and is well-suited to XG’s conditions. The overall method-selection error ($U_2 = 5.0\%$) arises mainly from the combined use of these distinct approaches and is lower than the theoretical error of any single method [18]. This error level falls within the range of high-quality ecosystem-service valuation studies [18,19] and is consistent with error characteristics in similar temperate-grassland accounting in northern China [37], supporting the robustness of the results.

In the uncertainty analysis, the 5.0% method-selection error is attributed to inherent theoretical assumptions in non-market valuation—such as the discrepancy between the industrial-substitution premise of the replacement cost method and the public-good nature of grassland services. By employing a combination of methods, the study reduced the one-sided bias from relying on a single approach. The 5.0% error thus reflects the combined residual bias of a multi-method strategy, demonstrating the practical benefit of methodological adaptation. This finding aligns with international evidence that coupling multiple valuation methods enhances the robustness of ecological accounting.

4.3. Data Verification: Enhancing Credibility Through Multi-Source Synergy

The core work regarding data was multi-source integration and cross-validation. This provided reliable support for indicator screening and method application through systematic

data underpinning, focusing on the solid implementation of foundational data. In terms of integration, a multi-source system was constructed using remote sensing inversion (500 m MODIS NPP), open-access datasets (CLCD land use, SRTM DEM, interpolated meteorological data), and field survey data. Remote sensing data provided spatialized ecological baselines. Open-access datasets ensured foundational support. Field survey data (e.g., agricultural product yields, tourist willingness-to-pay) corrected macro-statistical biases. This integration logic continues the established approach of multi-source data collaboration, merely optimizing the combination and verification methods for temperate grasslands. It conforms to the fundamental norms of “data triangulation” in international ecological accounting [20].

In the verification phase, reliability was strengthened through cross-validation and error quantification. Field-measured yields were compared and calibrated against official statistics (Xilingol League Statistical Yearbook 2024) to reduce systematic bias, and multi-source cross-validation mitigated interpolation errors. Additionally, sensitivity analysis clarified the influence of key parameters, while uncertainty analysis quantified errors from data resolution, method selection, and parameter variability, yielding a total error of $\pm 9.3\%$ and confirming acceptable results. These steps represent established practices; the present study’s contribution lies in their systematic alignment with region-specific accounting objectives, thereby enhancing the relevance and dependability of the data foundation. It should be noted that error estimation relied on Monte Carlo simulation (1000 iterations) and an error-decomposition model, whose accuracy depends on the definition of error sources and parameter-distribution assumptions. Future work could refine these estimates by increasing sample sizes and incorporating additional error components, such as model-structure uncertainty.

4.4. Policy Implications

Building on the valuation characteristics and methodological constraints identified for the XG protected area’s GEP, this study proposes the following localized pathways within the existing policy framework. These recommendations aim to enhance the scientific rigor, applicability, and long-term sustainability of ecological value transformation, ensuring they are grounded in the study’s findings and regional realities. First, a GEP-based ecological asset management system should be established. This system would involve the regular monitoring of dynamic trends in total GEP and its structural composition. Indicators such as the “relative increase in regulating service value” and the “achievement rate of region-specific indicators” should be integrated into assessments of ecological progress. Decision-making should account for the impacts of methodological limitations and fluctuations in core parameters, moving beyond a reliance on a single absolute GEP value. A focus on the stability and trends of regulating service values, in particular, aligns closely with the core needs of regional ecological conservation and barrier functions. Second, pilot initiatives for low-risk value transformation should be promoted in a scenario-specific manner. Leveraging the empirical validation of the 3M framework in temperate grassland ecosystems, priority should be given to core grassland services with high accounting precision and low uncertainty, such as carbon sequestration and water conservation. These can be linked to national carbon markets to develop grassland carbon-sink products, and trans-regional water-rights trading with beneficiary areas like Beijing–Tianjin–Hebei should be explored. The principle of “pilot-first and gradual expansion” is crucial; models developed for grasslands should not be indiscriminately applied to other ecosystem types, such as forests or wetlands, without proper adaptation. Third, ecology-prioritized “GEP+” green industries should be cultivated. The accounting results for cultural services can guide the development of high-end tourism products integrating “nomadic culture and nature

education,” implemented alongside strict adherence to ecological carrying-capacity controls. Furthermore, promoting “ecologically certified livestock products” can help ensure that value premiums are returned to local herders. This approach seeks to balance ecological contributions with community benefits, preventing a narrow focus on economic gains at the expense of ecological integrity and fostering a reciprocal relationship with the ecosystem. Fourth, dynamic policy optimization mechanisms must be strengthened. Following policy implementation, ecological compensation standards should be updated every 3–5 years based on dynamic monitoring data, observed value-change trends, and uncertainty analysis results. The interest-coordination mechanism for cross-regional ecological compensation needs continuous refinement. The long-term impacts of methodological limitations can be mitigated through strategies like “regular calibration” with updated local data, thereby better aligning policies with the principles of ethical fairness and ecological justice over time.

4.5. Research Limitations

The limitations of this study are as follows:

(1) Methodological Limitations

First, the valuation of regulating services predominantly relies on the replacement cost and shadow-project methods. Both approaches are inherently premised on industrial-substitution scenarios (e.g., valuing natural oxygen release by referencing industrial oxygen-production costs). A known challenge in ecological accounting is that such scenarios may deviate from the actual supply characteristics of ecosystem services—specifically, their public-good nature and reliance on long-term ecological sustainability—potentially leading to overstated values [42]. This issue is further exemplified by the “evapotranspiration–energy substitution” method used for climate regulation services. This method may not adequately capture the low-cost, public-good characteristics of natural regulation, nor does it define the actual geographic scope of beneficiaries, which could bias estimates toward their upper bound. Second, the analysis of spatial patterns was primarily descriptive. While spatial trends in ecosystem service values were mapped and described, a quantitative spatial correlation analysis with potential biophysical drivers (e.g., NPP, vegetation cover) was not conducted. Future studies could apply spatial econometric techniques, such as spatial autocorrelation analysis (e.g., Global and Local Moran’s I), geographically weighted regression (GWR), and hotspot/coldspot detection. This would enable a statistical examination of the relationships between service values and their drivers, helping to elucidate the mechanisms behind the observed spatial heterogeneity. Third, the transferability of the 3M framework is context-specific. The indicator system and methodological parameters were calibrated explicitly for temperate grassland protected areas. Direct application to regions dominated by other ecosystems (e.g., forests, wetlands) would require re-specification of core service indicators and valuation logic. Furthermore, the framework’s dependence on multi-source data integration and cross-validation means its effectiveness may be constrained in regions with poor data availability or underdeveloped monitoring systems, challenging the replication of the present validation approach.

(2) Limitations in Data Accuracy and Field Surveys

First, constraints in spatial and thematic data resolution affected local precision. The 500 m resolution of MODIS NPP data is insufficient to capture fine-grained heterogeneity in high-value, small-patch ecosystems like wetlands and sparse forests on sandy land, likely leading to an underestimation of their regulating service contributions. This is a key contributor to the quantified data-resolution error ($U_1 = 6.5\%$). Furthermore, classification ambiguities in the 30 m CLCD dataset (e.g., between sparse grassland and sandy land) can, after resampling, amplify valuation uncertainty along ecological transition zones,

introducing localized noise in the quantification of services like soil conservation. Second, key economic parameters were treated statically. Core valuation parameters, such as the carbon price and industrial electricity tariff, were based on cross-sectional market data from 2023–2024. Long-term market fluctuations and potential policy adjustments (e.g., carbon-trading mechanism reforms) were not modeled, which may affect the temporal stability and comparability of the monetary results over longer periods. Third, field survey data had temporal and sample size constraints. Although surveys covering tourist willingness-to-pay and agricultural outputs achieved spatial coverage of key areas, sampling was concentrated in the summer of 2025. The lack of multi-seasonal data collection, combined with a finite effective sample size, may introduce bias into the estimation of cultural service values, which can exhibit seasonal variability.

(3) Limitations of Temporal/Spatial Scope and Accounting Coverage

The study's scope presents three further considerations. First, by focusing monetization on a single year (2023–2024), the analysis provides a snapshot rather than a trend. The monetary values are sensitive to the policy and market conditions of that period, and their stability over longer economic or climatic cycles remains untested. Second, the empirical validation was confined to a grassland-type protected area. Other critical ecosystems within the broader protected area network, such as wetlands and forests, were not included, leaving the generalizability and necessary adaptations of the 3M framework across diverse ecosystem types unverified. Finally, an inherent philosophical limitation exists in reducing complex ecological values to a single monetary metric. This simplification risks overlooking non-market, intrinsic values embedded in biodiversity, such as habitat provision for endemic species or the preservation of genetic resources and cultural heritage. An over-reliance on economic valuation could inadvertently reinforce a utilitarian perspective, potentially sidelining deeper ecological and ethical considerations central to conservation. It may also fail to fully capture and incentivize the intrinsic motivation of local stewards, such as herders, whose long-term practices are vital for ecosystem integrity.

5. Conclusions

Based on the 3M framework—which integrates multi-dimensional (region-specific) indicators, multi-source data synergy, and multi-method adaptation—this study conducted a comprehensive ecosystem value assessment for the Xilingol Grassland National Nature Reserve. The case analysis provides the following key empirical insights and highlights their methodological implications:

- (1) Structure and characteristics of GEP in XG. The Gross Ecosystem Product (GEP) of the reserve was estimated at CNY 170.5229 billion. Regulating services constituted the overwhelming majority of the total value, with climate regulation alone contributing 93.9%. This result underscores the central role of regulating services—particularly climate regulation—in sustaining regional environmental stability within temperate grassland protected areas, while also highlighting that this predominance is contingent on the underlying industrial-substitution valuation scenario. In contrast, provisioning and cultural services accounted for only modest shares, reflecting the distinctive socio-ecological profile of the study area.
- (2) Methodological contribution: Regional adaptability is enhanced through the 3M framework. The case study demonstrates that the 3M framework facilitates the development of an indicator system closely aligned with local ecological and socio-economic contexts. This is achieved by focusing on locally salient outputs, prioritizing key regulating service indicators, and incorporating region-specific cultural values. The integration of field-survey data further enhanced the accuracy of valuing both

- provisioning and cultural services. Furthermore, the application illustrates how accounting methods, when differentiated and calibrated with local market parameters, can improve the regional representativeness and credibility of the valuation outcomes.
- (3) **Robustness of the accounting results.** Sensitivity analysis revealed that core parameters—such as the regional carbon-trading price and industrial oxygen-production cost—exerted a substantial influence on the total GEP, which is consistent with the dominant contribution of regulating services. Uncertainty analysis produced an overall error margin of $\pm 9.3\%$, which falls within the accepted range for ecological accounting and confirms the reliability of the estimates for XG.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Academic Committee of Central South University of Forestry and Technology (protocol code 20251215, 15 December 2025).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data used in this study come from legitimate publicly accessible sources. Core ecological accounting data were obtained from open-access public databases, with detailed acquisition and processing steps outlined in the “Section 2.2” section of the paper.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Full Name/Explanation
GEP	Gross Ecosystem Product
XG	Xilingol Grassland
MODIS	Moderate Resolution Imaging Spectroradiometer
NPP	Net Primary Productivity
DEM	Digital Elevation Model
GECP	Grassland Ecological Compensation Policy
RUSLE	Revised Universal Soil Loss Equation

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