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Analyzing Characteristics of Grassland Gross Ecosystem Product to Inform Decision Making in the Karst Desertification Control

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Abstract: Synergistically enhancing and realizing the value of grassland ecosystem services (ES) for economic activity is an important but challenging task for achieving sustainability in the karst desertification control (KDC). However, how to use grassland ES value characteristics in the KDC to make decisions on ES improvement, human well-being enhancement, and sustainable development remains unclear. In this paper, we took the contiguous region of karst desertification in Yunnan-Guangxi-Guizhou, China, a global hotspot, as the study area. Based on the valuation of the gross ecosystem product (GEP) and county economic intensity, we analyzed the structural and spatial characteristics of grassland GEP in the KDC using spatial analysis methods. We found that: (1) the grassland GEP in the KDC is mainly distributed in counties with low economic intensity (86.05% of the total number of counties) and vulnerable to losses caused by the livelihood of farmers; (2) the grassland GEP in the KDC is spatially small and scattered (the geographic concentration lies between 0.015 and 0.237), which makes it difficult to form industrial scale advantages; (3) the public product index (66.22–96.77%) and industry scale concentration (97.87–99.86%) of grassland GEP in the KDC are high, and most of the GEP is difficult to transform on the private market. Based on our findings, we proposed three corresponding recommendations for economic decision-making. The results of this study can provide a reference for economic decision-making regarding the management of grassland ES in karst areas with similar conditions and beyond.

Keywords: gross ecosystem product; valuation; grassland; karst desertification control; economic decision

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1. Introduction

Karst regions cover approximately 20% of the world's dry ice-free land [1]. Various types of karst have been widely developed in China. It covers about 36% of the national territory [2]. The South China karst, centered on the Guizhou Plateau, is the largest area of exposed carbonate rocks amoung the three main concentrated karst areas in the world, with a karst area of 555,000 km^2 [3]. Karst ecosystems have a binary three-dimensional spatial structure coupled with unique hydrological and geological conditions [4], forming a fragile, sensitive, and vulnerable ecological environment [5]. In the context of high population pressure and limited livelihoods, the ecosystem is unduly disturbed by traditional industries [6], resulting in the globally representative and typical ecosystem problem of karst desertification [7,8]. Karst desertification is an extreme manifestation of land degradation [9]. It affects the supply of ES and forms a poverty trap [10], which in turn threatens human well-being.

As a pioneer community ecosystem for alleviating severe karst desertification and restoring degraded land [11], grasslands not only provide an ecological security shield for regional sustainable development but also contribute to household livelihoods through forage supply and grazing [12,13]. Since the 1990s, grassland establishment and herbivorous animal husbandry development have been regarded as the main projects for controlling karst desertification [14]. For example, in the early stages of the KDC, the whole society generally attached importance to the livestock support services provided by grasslands [15] due to the fact that these services can be traded on private markets or contribute to livelihoods for local residents. In the context of an understanding that the pursuit of ecological material goods is dominant, grass cultivation and livestock breeding became the main modes of KDC. Accordingly, it not only promoted the greening of vegetation [16–18] but also improved the diversity of household livelihoods [19]. As research has progressed, researchers have generally recognized that karst is a complex ecosystem, and its internal elements are not a single cause-and-effect relationship but a complex feedback [20]. Therefore, in the later period of the KDC, the structure, function, and process of karst ecosystems are of great concern by relevant scholars [21]. Correspondingly, the objectives of engineering measures for the management of karst desertification are gradually oriented towards the overall improvement of grassland ES. For example, increasing species diversity in grasslands by selecting pioneer species (e.g., legumes) and optimizing community configuration [22,23]; stimulating plant growth and increasing herbaceous biomass by adding nutrients (e.g., N, P, and K) during grassland establishment and management [24]; and improving the health index of grassland ecosystems through engineering measures such as returning farmland to grassland or establishing artificial grasslands [25]. After decades of engineering management, a special grassland ecosystem (hereinafter referred to as grassland in the KDC) has been formed correspondingly. Now, in response to the major needs of the United Nations Decade on Ecosystem Restoration (2021–2030) [26], the objectives of ecosystem conservation and restoration of grassland in the KDC have shifted from the initial pursuit of vegetation greening to the synergistically comprehensive enhancement of ES and human well-being [27]. Quantifying the contribution of the ES value of grasslands in the KDC to people and incorporating it into economic decision making is an important step towards achieving this goal.

In previous research, researchers have generally accounted for the physical quantities of individual ES in karst areas based on biophysical and monetary measures. For example, the accounting cases of water yield, soil conservation, and carbon sequestration in typical karst areas in southwest China [28–30]. Meanwhile, some scholars have also used the value transfer method to evaluate the value of each karst ES. For instance, Hu et al. [31], Wang et al. [32], and Zhang et al. [33] took the karst-Beibu Gulf of southwest Guangxi, the Yunnan-Guizhou Plateau, and China, respectively, as the study areas to estimate the ES value of karst ecosystems. From the perspective of karst area to global grassland ecosystem, researchers have widely discussed the monetary value of grassland ES from the aspects of index system, value accounting method, influencing factors, and land-use management. Richter et al. summarized 29 indicators and 85 methods of grassland ES value accounting [34]. Chen et al. discussed the influencing factors by analyzing the temporal and spatial changes based on grassland ES value accounting [35]. Rao et al. calculated the ES value of grasslands in semi-arid areas to guide land-use management [36]. From these typical cases, researchers universally apply comparative analysis of ES values, either vertically (e.g., time, space) or horizontally (e.g., compared with GDP), to inform management decisions on ES and land use by analyzing ES trade-offs and synergistic relationships, driving mechanisms, etc. However, a thematic valuation of grassland ES values in the KDC is rare, and no researchers have analyzed the structural and spatial characteristics of the ES values of grasslands in the KDC and proposed valuable economic decision suggestions. More notably, previous valuations have focused on ecological attributes and paid insufficient attention to economic attributes and their utility. In addition, decisions have not taken into account local economic strengths, resulting in the suspension of economic decisions to improve ES and human well-being.

In this study, we took the concentrated contiguous area of karst desertification in Yunnan-Guangxi-Guizhou, China as the study area, where the regional characteristics and engineering measures are typical and representative globally. According to the background of the study area, we propose the following theoretical hypotheses of the characteristics of grassland ES value in the KDC (Figure 1): (1) The ES value of grassland in the KDC was mainly concentrated in the mountainous area far from the city, and the farther from the city, the higher the ES value. (2) For the structure and classification of grassland ES value in the KDC, the value of regulation services accounts for the majority proportion (the value is difficult to translate through the market due to its public nature and externalities), and the value of ecological material goods and services that can be directly traded based on the private market accounts for a small proportion. (3) Owing to the small scattered landscape pattern of grassland in the KDC, the geographical concentration of ES value is low, and it is difficult to form an industrial scale advantage. According to the theoretical assumptions, we applied the GEP accounting framework, a method to assess the value of nature's contribution to economic activity [37,38], to quantify the value of grassland ES in the KDC. On the basis of accounting for the counties' economic intensity, we analyzed the structural and special characteristics of the grassland GEP using the geospatial analysis method and proposed some economic decision recommendations for the management of the grassland ES in the KDC.

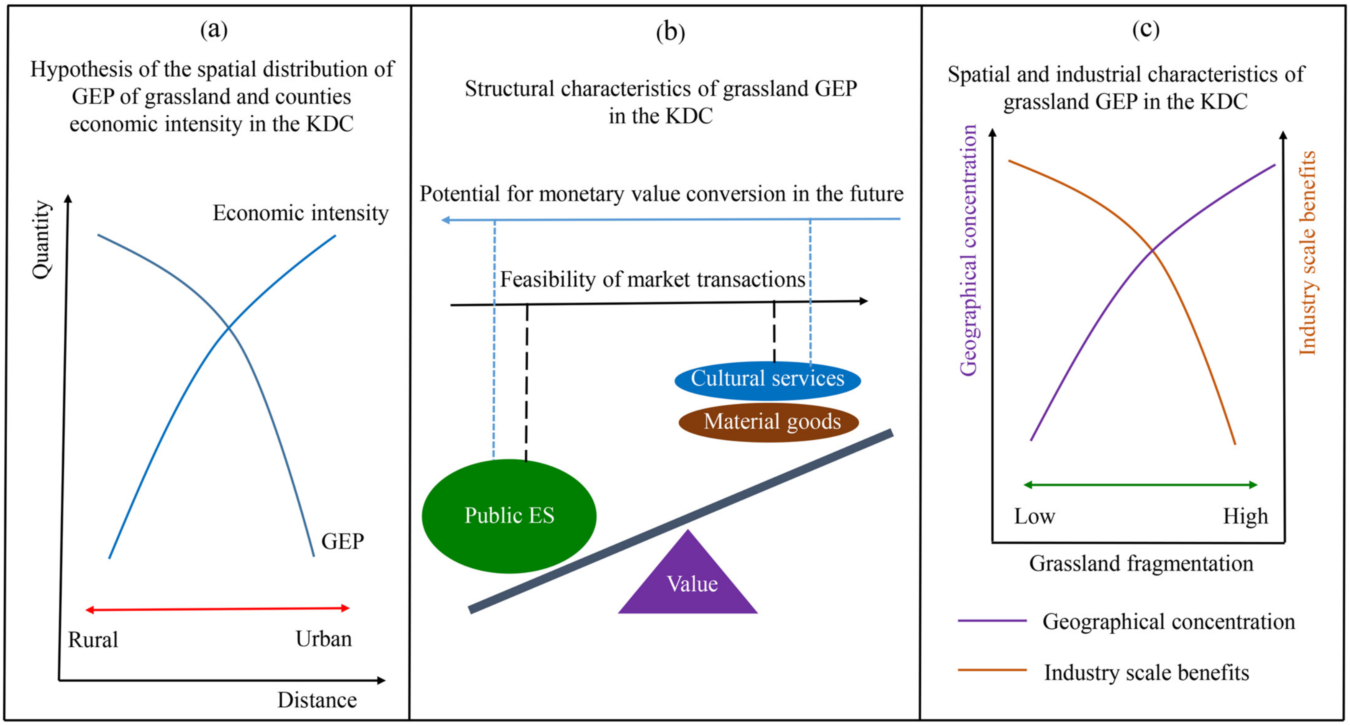

Figure 1. Theoretical hypothesis of GEP characteristics of grassland in the KDC.

Through the GEP valuation of grasslands in the KDC, researchers and stakeholders can better understand the economic value of grassland ES in the KDC. More importantly, we proposed differentiated recommendations for managing grassland ES in the KDC in relation to county economic strength, which can improve the feasibility of economic decision-making processes. At the same time, this study shifts from the previous bio-physical assessment that focused on ecological attributes and their intrinsic values to an assessment that focuses on economic attributes and their utility values, while bridging the knowledge gap between previous studies on ES management decisions that lacked actionability because they did not consider local input potential. Going forward, this study can provide theoretical references for the implementation of major projects to protect and restore grasslands in ecologically fragile areas (especially karst areas with the same ecological and environmental conditions), the realization of the grassland eco-products value, and rural revitalization.

2. Materials and Methods

In this paper, we first selected the globally representative and typical hot study area of the KDC. On this basis, we followed the logical threads of basic geospatial data and socioeconomic collection—GEP and economic intensity index accounting—GEP characteristic analysis—decision making (Figure 2). In particular, we applied national and local standards (or specifications) to calculate the GEP of grasslands in the KDC. Finally, we used SPSS 2019 (version 19.0; SPSS, Chicago, IL, USA) to analyze the indicators and used ArcGIS 10.3 (Redwood City, CA, USA) and Originlab Origin 2021 (Northampton, MA, USA) to visualize the data.

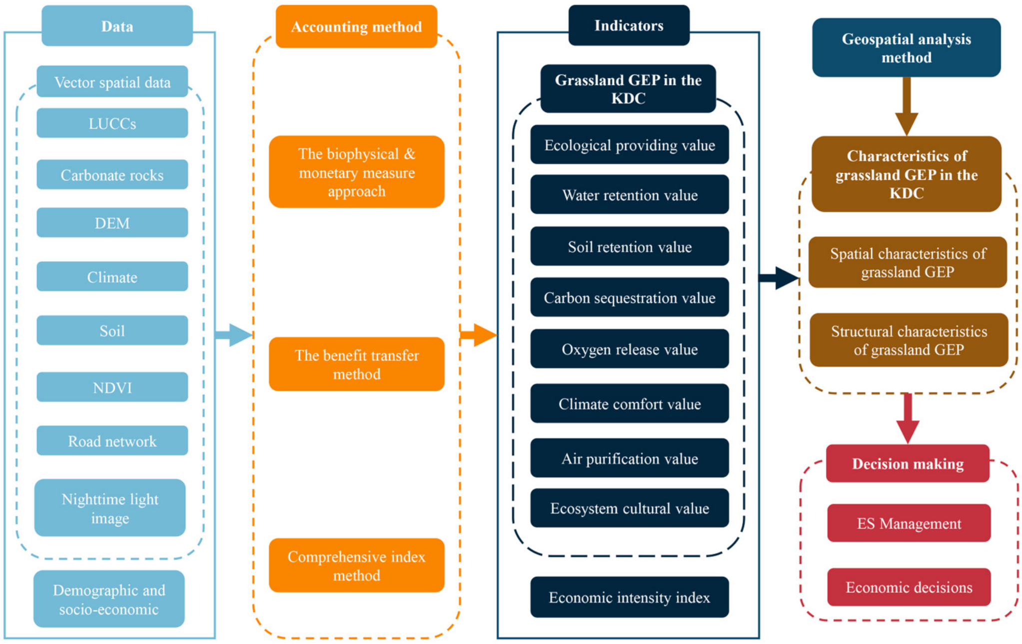

Figure 2. The flow chart of research methodology and logical threads.

2.1. Research Areas

The concentrated contiguous area of karst desertification in Yunnan-Guangxi-Guizhou is located at the intersection of Yunnan Province, Guangxi Zhuang Autonomous Region, and Guizhou Province, China (97°21′–117°19′ E and 20°13′–34°19′ N) (Figure 3). It includes 91 counties (among which 5 counties have no karst grasslands, and the following data of grassland ES in KDC are calculated based on 86 counties). In the region, most of the sites are located in the southeastern part of the Yunnan-Guizhou Plateau. It is a transition zone to the Guangxi Basin and borders Vietnam to the south, which is a typical tectonic plateau mountainous area. It includes six topographic zones, namely, karst plateau, karst fault basin, karst peak cluster depression, karst peak forest plain, karst gorge, and karst trough valley. At the same time, this area is also an important ecological functional area in the Pearl River and Yangtze River basins. The study area covers 228,000 km^2, of which 135,300 km^2 is karst area, accounting for 59.34% of the total area; karst grassland is 22,000 km^2, accounting for 16.26% of the karst area and 9.7% of the total area. The region is a tropical and subtropical monsoon zone. Due to the altitude difference in the region, the climate has the characteristics of both low-latitude monsoon and mountain plain climates, with annual precipitation ranging from 880 to 1991 mm, mainly concentrated in the months of April–September. The population of the region is 24.6 million, and the GDP reaches CNY 398.89 billion in 2020.

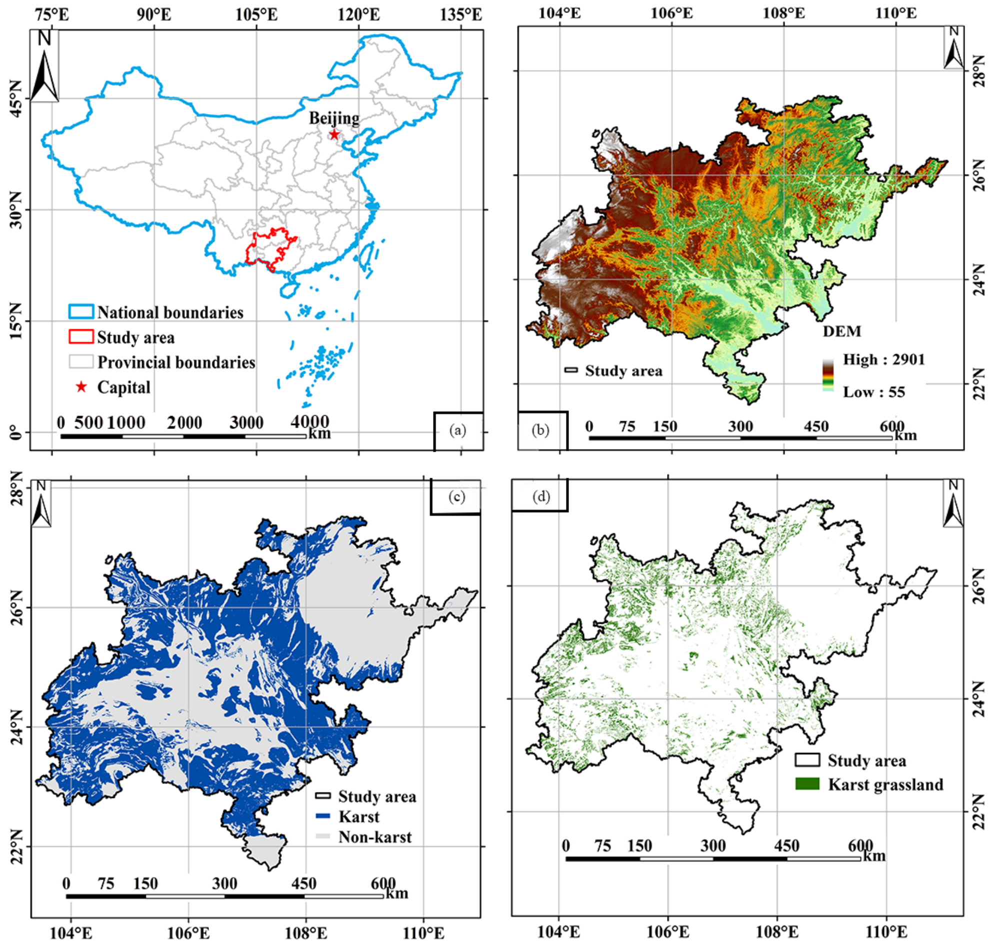

Figure 3. Study area: (**a**) Location of study area; (**b**) the DEM of the study area; (**c**) Karst distribution; and (**d**) Grassland distribution in the KDC area.

In recent years, the study area has carried out a number of national projects to combat karst desertification and alleviate poverty. For example, in February 2008, China's State Council approved the "Comprehensive Management Plan for the Control Karst Desertification in the Karst Region (2006–2015)", which plans to carry out comprehensive management in 100 pilot counties in eight provinces in southern China during the Eleventh Five-Year Plan. Pilot projects were carried out in 38 counties in the study area [39]. Based on this, the Chinese government implemented the "Thirteenth Five-Year Plan for the Construction of a Comprehensive Management Project for Karst Desertification" in 2016 [40]. After two phases of karst desertification management, all karst counties (karst area of more than 30% of the national territory) in the study area were fully covered. At the same time, the Chinese government has implemented the "Plan for Regional Development and Poverty Alleviation in the Contiguous Karst Desertification Region of Yunnan-Guangxi-Guizhou (2011–2020)" [41]. By the end of 2020, all counties in the study area were lifted out of poverty.

The grassland ecosystem of the concentrated contiguous area of karst desertification in Yunnan-Guangxi-Guizhou, China, not only has the basic attributes of fragility, sensitivity, and vulnerability, but is also characterized by high population pressure, numerous ethnic minorities, and lagging industrial development [42]. What's more, the spatial heterogeneity of the region is extremely significant. Compared to other non-karst regions, especially in relation to globally important rangelands, the grassland ecosystems in this region are more complex and the ES value is more difficult to realize. Many issues about the value realization of grassland ES globally (especially in karst areas) can be answered in this region. It can be seen that the study area is typical and representative.

2.2. Data Source

The data and sources are shown in Table 1.

Table 1. Data, resolution, and sources in study area.

Data	Resolution	Source
Land Use (grassland)	30 m	Resource and Environment Science and Data Center, https://www.resdc.cn (accessed on 13 December 2022)
Carbonate rocks	1:500,000	Karst Science Data Center, Institute of Geochemistry Chinese Academy of Sciences
DEM	30 m	Resource and Environment Science and Data Center, https://www.resdc.cn (accessed on 5 December 2022)
Meteorological data	1 km	(1) National Meteorological Science Data Center, https://data.cma.cn (accessed on 3 December 2022). (2) National Qinghai-Tibet Plateau Scientific Data Center, http://data.tpdc.ac.cn/zh-hans/ (accessed on 15 December 2022). (3) National Earth System Science Data Center, https://www.geodata.cn (accessed on 5 December 2022).
Soil	1 km	Harmonized World Soil Database (HWSD) http://www.ncdc.ac.cn/portal/metadata/fcd60332-575c-4209-ae9c-d1efc1f424d4 (accessed on 5 December 2022)
NPP	1 km	Resource and Environment Science and Data Center, https://www.resdc.cn (accessed on 5 December 2022)
Administrative Boundaries	--	Resource and Environment Science and Data Center, https://www.resdc.cn (accessed on 5 December 2022)
Road network data	1 km	Geographic remote sensing ecological network platform, www.gisrs.cn (accessed on 7 May 2023)
Demographic and socioeconomic data	--	(1) Statistical Yearbook (Province, City, County, District); (2) Government Statistical Bulletin of National Economic and Social Development (County, District); (3) Annual Government Work Report (County, District); (4) Seventh National Census Bulletin (China); (5) Missing Data: Obtained by the linear interpolation method. Prioritization hierarchy of the same indicator acquisition: (1) > (2) > (3) > (5)
Nighttime light	0.44 km	National earth system science data center, https://www.resdc.cn (accessed on 8 December 2022)

2.3. Evaluation and Analysis Methods

2.3.1. Measuring GEP of Grassland in the KDC

- Ecosystem providing value

Considering that the grazing output value of grassland in the KDC is not based on natural boundary statistics, the theoretical value of grazing yield of karst grassland is used as the basis for accounting. The formula is:

$$V_M = E_P \times A_G \tag{1}$$

where V_M is the value of material goods of grassland in the KDC (CNY); E_P refers to the value of ecological material goods per unit of grassland area (CNY·hm^{-2}). According to the research results of Shen et al. [43], we take 1.07 cattle/hm^2. The price of cattle is based on the "National Agricultural Product Cost-Benefit Compilation-2021" [44], which is calculated at 16,713.15 CNY per cattle. A_G is grassland area (hm^2).

- Ecosystem regulation services value

1. Water retention value

Estimation of supply. Following the principle of water balance, water retention was calculated using the InVEST model (with two modules for water yield and water retention). The formula for measuring water yield can be expressed as follows:

$$Y_x = (1 - \frac{AET_x}{P_x}) \times P_x \tag{2}$$

where Y_x (mm·yr^{-1}) is the water yield for pixel x, AET_x (mm·yr^{-1}) is the actual annual evapotranspiration for pixel x, and P_x (mm·yr^{-1}) is the annual precipitation for pixel x.

Since actual annual evapotranspiration is difficult to measure accurately, the evapotranspiration portion of the water balance, $\frac{AET_i}{P_i}$, is based on an expression of the Budyko curve.

$$\frac{AET_x}{P_x} = 1 + \frac{PET_x}{P_x} - \left[1 + \left(\frac{PET_x}{P_x}\right)^{W_x}\right]^{\frac{1}{W_x}} \tag{3}$$

$$W_x = Z \times \frac{AWC_x}{P_x} + 1.25 \tag{4}$$

$$PET_x = K_{c_x} \times ET_0 \tag{5}$$

Here, PET_x is potential evapotranspiration (mm·yr^{-1}); W_x is a non-physical parameter that represents natural climate-soil properties; Z is a dimensionless constant ranging from 1 to 30 and follows local precipitation and hydrogeological characteristics, AWC_x is plant-available water content (mm); ET_0 is the reference evapotranspiration of pixel x and represents the coefficient of vegetation evapotranspiration associated with pixel x' and K_{c_x} is the evapotranspiration coefficient for pixel x.

Then, water retention is calculated using the following formula:

$$WR = \min\left(1, \frac{249}{Velocity}\right) \times \min\left(1, \frac{0.9 \times TI}{3}\right) \times \min\left(1, \frac{Ksat}{300}\right) \times Y_x \tag{6}$$

$$TI = \log\left(\frac{DrainageArea}{SoilDepth \times Percent\_slope}\right) \tag{7}$$

where WR represents water retention (ton·yr^{-1}); $Velocity$ is velocity coefficient; TI refers to topographic index; $Ksat$ is soil saturated hydraulic conductivity; Y_x is water yield (mm·yr^{-1}); $DrainageArea$ is catchment area of pixel x; $SoilDepth$ is soil depth; and $Percent\_slope$ is percent slope.

Value accounting. The calculation formula is:

$$V_{\mathrm{wr}} = P_{\mathrm{wr}} \times WR \tag{8}$$

where V_{wr} represents the total value of water retention (CNY); P_{wr} is the price of water resources, using the average water price (2.28 CNY·ton^{-1}) of 31 provincial capitals in Mainland China in 2020 with data from the China Water Price Network, www.h20-china.com/price/ (accessed on 13 January 2023); and WR represents water retention (ton·yr^{-1}).

2. Soil retention value

Estimation of supply. Soil retention refers to the ability of an ecosystem to regulate soil erosion and sediment interception, which plays a key role in maintaining land productivity. It can be calculated by using the revised universal soil loss equation (RUSLE), and the formula can be expressed as:

$$Q_{\mathrm{sr}} = R \times K \times L \times S \times (1 - C \times P) \tag{9}$$

Q_{sr} is soil retention (t/a), R, K, L, S, C and P is rainfall erosivity, soil erodibility factor, terrain factor, vegetation cover and management factor, and soil and factors for water conservation measures, respectively. The calculation methods of R, K, L, S, C, and P refers to Xu et al. [45].

Value accounting. Using an alternative cost method. The calculation formula is:

$$V_{SC} = V_1 + V_2 \tag{10}$$

$$V_1 = (Q_{SR}/\rho) \times r \times \beta_1 \tag{11}$$

$$V_2 = \sum (Q_{OI}/r_i) \times \beta_{4i} \tag{12}$$

$$Q_{OI} = Q_{SR} \times C_i \tag{13}$$

where V_{SC} is the total value of soil conservation of grassland in the KDC (CNY); V_1 and V_2 are the values of sedimentation reduction and fertility retention, respectively (CNY); Q_{SR} is the amount of soil retention (ton); and ρ is the soil capacity. Referring to "the Technical Guide to Accounting for Gross Ecosystem Product" (hereinafter referred to as "GEP specification") [46], the average soil capacity of Yunnan, Guizhou, and Guangxi, China was taken to be 1.23 t·m^{-3}. r refers to the percentage of sediment lost to soil erosion that is silted up in reservoirs, rivers, and lakes (%). Referring to "the specification of grassland ecosystem service function assessment" (hereinafter referred to as "grassland specification") [47], we taken 0.24; β_1 is the cost of the unit storage capacity project, taken to be 42 CNY·ton^{-1}; Q_{OI} is annual fertilizer retention (ton·yr^{-1}); C_i is the N, P, K, and organic matter content of the soil (%); $r_{\rm i}$ is N, P, K, and organic matter content in fertilizer and organic matter (according to the "grassland specification" 14%, 15%, 50%, and 100% were taken, respectively); and β_2 is the value of chemical fertilizer and organic matter (CNY·ton^{-1}). According to the "grassland specification": diammonium phosphate contains 14% of nitrogen and 15.01% of phosphorus and potassium chloride contains 50% potassium content. The price of diammonium phosphate is 3060 CNY·t^{-1}, the price of potassium chloride fertilizer is 2350 CNY·t^{-1}, and the price of organic matter is 855 CNY·t^{-1}.

3. Carbon sequestration and storage value

Estimation of supply. The net ecosystem productivity method was used. The formula is:

$$Q_{tCO_2} = M_{CO_2} \times NEP \tag{14}$$

$$NEP = \alpha \times NPP \tag{15}$$

where Q_{TCO_2} is the carbon sequestration in grasslands in the KDC (ton); $M_{CO_2}/M_C = 44/12$, which is the coefficient of conversion of C to CO_2; NPP is net primary productivity (t·C·yr^{-1}); and α is the conversion coefficient between NEP and NPP, which is assumed to be 0.1532 according to the "GEP Specification".

Value accounting. The calculation formula is:

$$V_{CO_2} = Q_{tCO_2} \times P_{CO_2} \tag{16}$$

V_{CO_2} is the value of carbon sequestration of GKD (CNY); Q_{tCO_2} is the amount of carbon sequestered by grassland in the KDC (ton); and P_{CO_2} is the market price of carbon trading. The average price (33.6 CNY·t^{-1}) of eight Chinese trading markets (Beijing, Fujian, Guangdong, Hubei, Shanghai, Shenzheng, Tianjin, and Chongqing) was taken from China Carbon Trading Network (www.tanjiaoyi.com (accessed on 6 January 2023)) in 2020.

4. Oxygen release value

Estimation of supply. According to the chemical equation of photosynthesis, for every 1 mole of CO_2 produced and absorbed, the plant releases 1 mole of O_2. The calculation formula is:

$$Q_{\rm op} = M_{O_2}/M_{CO_2} \times Q_{CO_2} \tag{17}$$

where $Q_{\rm op}$ is the amount of oxygen released from grasslands in the GKD (ton·O_2·yr^{-1}); $M_{O_2}/M_{CO_2} = 32/44$, which is the coefficient of conversion of CO_2 to O_2; and Q_{CO_2} is the amount of carbon sequestered by grasslands in the KDC (ton·C·yr^{-1}).

Value accounting. The market value method was used. The calculation formula is:

$$V_{\text{op}} = Q_{op} \times C_O \tag{18}$$

V_{op} is the value of oxygen release ($CNY \cdot yr^{-1}$); Q_{op} is the amount of oxygen released ($t \cdot O_2 \cdot yr^{-1}$); and C_O is the price of industrial oxygen production, taken to be 1462.35 $CNY \cdot ton^{-1}$ (data from "Grassland Specification").

5. Climate comfort value

Estimation of supply. The total energy consumed by ecosystem evapotranspiration was chosen as the valuation index for the physical extent of climate regulation services provided by grasslands in the KDC. The formula is:

$$E_{pt} = EEP \times S \times D \times 10^6 / (3600 \times r) \tag{19}$$

E_{pt} is the total energy consumed by transpiration and evapotranspiration on the grassland in the KDC ($kW \cdot h \cdot yr^{-1}$); EEP is the heat consumption per unit area of transpiration on the grassland in the KDC ($kJ \cdot m^{-2} \cdot d^{-1}$); S, D is the area of the grassland ecosystem, the number of days with a daily maximum temperature of 26 °C or more, respectively; and r is the air-conditioning energy efficiency ratio, taken to be 3.0, dimensionless.

Value accounting. The value of climate comfort of grasslands in the KDC is calculated using the alternative cost method, i.e., the cost of electricity needed to artificially regulate temperature and humidity. The formula is:

$$V_{pt} = E_{pt} \times P_e \tag{20}$$

V_{pt} is the climate comfort value of grassland in the KDC ($CNY \cdot yr^{-1}$); E_{pt} is the total energy consumed by grassland in the KDC to regulate climate ($kW \cdot h \cdot yr^{-1}$); P_e is the local consumer electricity price, using the average electricity price of Yuannan, Guangxi, and Guizhou, China, in 2020, data is from China's electricity price check system, http://cep.cec.org.cn/ (accessed on 11 January 2023), taken to be 0.51 $CNY \cdot kW^{-1} \cdot h^{-1}$.

6. Air purification value

Estimation of supply. Considering the characteristics of small and scattered grasslands in the KDC, the air purification capacity of the grassland ecosystem was chosen to estimate the physical volume. The calculation method is:

$$Q_{ap} = \sum_{i=1}^{n} Q_i \times A \tag{21}$$

where Q_{ap} is the amount of air purification in grassland in the KDC ($ton \cdot yr^{-1}$); n is the number of air pollutant categories; i is an air pollutant category, I = 1, 2, 3, ... n; and Q_i is the cleaning purification volume of air pollutants of category i per unit area ($t \cdot km^{-2} \cdot yr^{-1}$). According to the "Gross Eco-products accounting specification (hereinafter referred to as "eco-products specification") [34], SO_2, NO_x, and dust purification were 2.94 $t \cdot km^{-2} \cdot yr^{-1}$, 1.57 $t \cdot km^{-2} \cdot yr^{-1}$, and 8.41 $t \cdot km^{-2} \cdot yr^{-1}$, respectively. A is the area of grassland in the KDC (km^2).

Value accounting. The value of air purification of grasslands in the KDC was accounted for using the substitution cost method (i.e., the cost of industrial treatment of air pollutants). The calculation formula is:

$$V_{ap} = Q_{ap} \times c_i \tag{22}$$

V_{ap} is the value of air purification of grassland in the KDC ($CNY \cdot yr^{-1}$); Q_{ap} is the amount of air purification of grassland in the KDC ($ton \cdot yr^{-1}$); and c_i is the treatment cost unit of air pollutant category i ($CNY \cdot ton^{-1}$), according to "grassland specification". The treatment cost of SO_2, NO_x, and dust are 1.28 $CNY \cdot kg^{-1}$, 1.41 $CNY \cdot kg^{-1}$, and 0.33 $CNY \cdot kg^{-1}$, respectively.

- Ecosystem cultural services value

Since the cultural value of non-karst grasslands is not included in the calculation, it is difficult to accurately distinguish the cultural value of grassland in the KDC independently. Here, the equivalent factor method is used for the calculation. The formula is:

$$V_{cp} = A_i \times D \times E_{vpa} \tag{23}$$

$$D = S_r \times F_r + S_w \times F_w + S_c \times F_c \tag{24}$$

where V_{cp} is the cultural service value of grassland in the KDC (CNY); A_i is the grassland area of the i-th county in the KDC (hm^2); D is the cultural service value equivalent per unit area of grassland in the KDC ($CNY \cdot hm^{-2}$); S_r, S_w, and S_c are rice, wheat, and corn as the percentage of the sown area of the three crops in 2020, respectively (%), taken from China's annual average data from 2016 to 2020 and data from "China Statistical Yearbook"; F_r, F_w, and F_c represent the average profit per unit area in 2020 for rice, wheat, and corn, respectively ($CNY \cdot hm^{-2}$), taken from China's annual average data from 2016 to 2020 and data from "National Agricultural Product Cost-Benefit Compilation-2021"; and E_{vpa} is the landscape's aesthetic value equivalent per unit area of grassland, based on the research results of Xie et al. [48], taken to be 0.96.

2.3.2. Evaluation of Counties Economic Intensity

- Structure of indicator system

In accordance with the purpose of the indicator system, which is used to reflect the degree of regional economic development, and in conjunction with the possibility of data acquisition, the following 15 indicators (Table 2) were used as indicators of economic intensity at different levels of the county.

Table 2. The indicators system and weights of counties economic intensity.

Number	Indicators	Unit	Weight
X1	Economic density	10,000 CNY/km^2	0.1057
X2	Per capita GDP	CNY/capita	0.0317
X3	The proportion of the output value of secondary and tertiary industries in GDP	%	0.0200
X4	Local general public budget revenue per capita	CNY/capita	0.0743
X5	General public budget expenditure per capita	CNY/capita	0.0228
X6	Per capita household savings deposit balance	CNY/capita	0.0465
X7	Per capita year-end loan balances of financial institutions	CNY/capita	0.0698
X8	Number of industrial enterprises above designated size per 10,000 people	Num/10,000 capita	0.0952
X9	Number of fixed-line telephone users per 100 people	Households/100 capita	0.0601
X10	Urbanization rate	%	0.0407
X11	Per capita total retail sales of consumer goods	CNY/capita	0.0619
X12	Per capita disposable income of urban households	CNY/capita	0.0253
X13	Per capita disposable income of rural households	CNY/capita	0.0658
X14	Nighttime light index	--	0.0394
X15	Highway density	Km/km^2	0.2406

- Standardization of data.

Since the units of the indicators are not uniform and there is a lack of comparability among the indicators, the entropy value method was used to standardize the 15 indicators. Since the selected indicators are all positive indicators, the following formula is used for calculation and processing.

$$X'_{ij} = \frac{X_{ij} - \min(X_{ij})}{\max(X_{ij}) - \min(X_{ij})} \tag{25}$$

where X'_{ij} is the standardized value of the j-th indicator for the i-th county; X_{ij} is the actual value of the j-th indicator for the i-th county; $\max(X_{ij})$ is the maximum value of the *j*-th indicator in the county; and $\min(X_{ij})$ is the minimum value of the *j*-th indicator in the county.

- Determination of weights

The entropy value method was used for calculation, and the calculation process was as follows:

First, calculate the weight of the j-th indicator for the i-th county.

$$Y_{ij} = \frac{X_{ij}}{\sum\limits_{i=1}^{n} X_{ij}} \tag{26}$$

Second, account for the entropy value of the *j*-th indicator.

$$e_i = -k\sum_{i=1}^{m} Y_{ij} \ln Y_{ij} \tag{27}$$

Third, determine the weights of each indicator.

$$W_j = \frac{1 - e_i}{\sum\limits_{i=1}^{n} 1 - e_i} \tag{28}$$

Finally, perform a composite index calculation as follows:

$$I_i = \sum_{j=1}^{n} W_j \times X_{ij} \tag{29}$$

In Equations (26)–(29) above, Y_{ij} denotes the weight of the *j*-th indicator of the *i*-th county, *n* indicates the number of counties, e_i is the entropy value, $k = \frac{1}{\ln m}$, m is the number of indicators, W_j is the indicator weight, and I_i denotes the economic intensity index of the *i*-th county.

The specific index weights are shown in Table 2. Among the 15 indicators, the economic density and highway density have a higher weight because the higher the density of the county economy, the more frequent the economic activity, and the more vigorous the demand and consumption of ES. At the same time, there are also funds, technology, and labor inputs to protect the ecological environment; in particular, it is beneficial to promote the transformation of ES into ecological funds and realize the value of the grassland ES in the KDC. Highway density is an important index that reflects transportation accessibility. The higher the highway density, the faster and more convenient the material flow, information flow and capital flow in the county, and the more beneficial it is to improve the value realization rate of the grassland ES in the KDC.

2.3.3. Characteristic Quantification of Grassland GEP in the KDC Area

- Structural characteristic of grassland GEP in the KDC area

Public eco-products index. It is used to reflect the size of the proportion of public eco-products. The larger the share, the more prominent the regional ecological function, the lower the degree of marketability, and the more necessary it is for both the government and market instruments to increase the value realization rate of ES. The formula is:

$$R_{EVR} = \frac{ERV}{GEP} \tag{30}$$

where R_{EVR} and ERV refer to the public eco-products index and ecosystem regulation services, respectively.

Industrial scale concentration index. It is used to reflect the degree of industry aggregation. The formula is:

$$CR_5 = \frac{\sum_{i=1}^{5} GEP_i}{GEP} \tag{31}$$

where CR_5 is the concentration index of the industrial scale (%), which is the ratio between the value of the five largest categories of ES and the GEP; $\sum_{i=1}^{5} GEP_i$ is the sum of the values of the five largest ES (10,000 CNY); and GEP is total value of grassland ES in the GKD (10,000 CNY).

- Geospatial characteristics of grassland GEP in the KDC

We use geographic concentration as a metric. The Herfindahl index is used to reflect the spatial concentration of the GEP. The more concentrated the spatial distribution of the GEP, the more limited the relative beneficiaries. However, for two regions with comparable total GEP, the smaller the Herfindahl index, the more beneficial it is to improve the equalization and effectiveness of ecological well-being.

$$G_h = \sum_{k=1}^{n} Sk^2 - \frac{1}{K} \tag{32}$$

where G_h is the Herfindahl index; S_K is the share of GEP in the total GEP for the k-th region; and K is number of regions.

2.3.4. Spatial Autocorrelation Analysis

The Moran index is used to analyze the autocorrelation of the counties in the study area, and the formula is as follows:

$$Moran'sI = \frac{\sum_{j}^{n} \sum_{j=i}^{n} (x_i - \overline{x})(x_j - \overline{x})}{S^2 \sum_{j}^{n} \sum_{j=i}^{n} w_{ij}} \tag{33}$$

where w_{ij} is the proximity relationship between county i and county j; n is the number of counties; x_i is the value of the ith county; x_j is the value of the jth county; and $Moran'sI$ takes values between -1 and 1, and negative, positive, and 0 represent negative correlation, positive correlation, and no correlation, respectively.

2.3.5. Indicator Analysis Method

The comparative mean method was used in IBM SPSS Statistics 19.0 (version 19.0; SPSS, Chicago, IL, USA) to analyze the distribution dynamics of the industrial characteristics of the grassland ES in the KDC, with indicators including mean, standard deviation, median, skewness, and kurtosis.

3. Results

3.1. Spatial Distribution of Grassland GEP and County Economic Intensity in the KDC

In 2020, the GEP of the grassland in the KDC of the study area reached CNY 499.81 billion. Among the 86 counties, the GEP lies between CNY 0.07 and 25.52 billion (Figure 4a), with a highly positive skewed, low kurtosis distribution, and most counties (80.23%) were below CNY 10 billion (Table 3). In terms of spatial distribution, the GEP was mainly distributed in the central and western regions of the study area, with the trend of West > Central > East. This distribution trend is closely related to the distribution of grasslands in the KDC. Its western fringe areas have a higher GEP value, such as Pingbian Miao Autonomous County (CNY 25.52 billion), Shuicheng District (CNY 25.42 billion), and Maguan County (CNY 23.65 billion). The eastern fringe areas have a lower GEP value, such as Jinping County (CNY 0.022 billion), Ziyuan County (CNY 0.013 billion), and Jianhe County (CNY 0.007 billion), etc. Moreover, the GEP increases with outward distance, centering on the location of the city government.

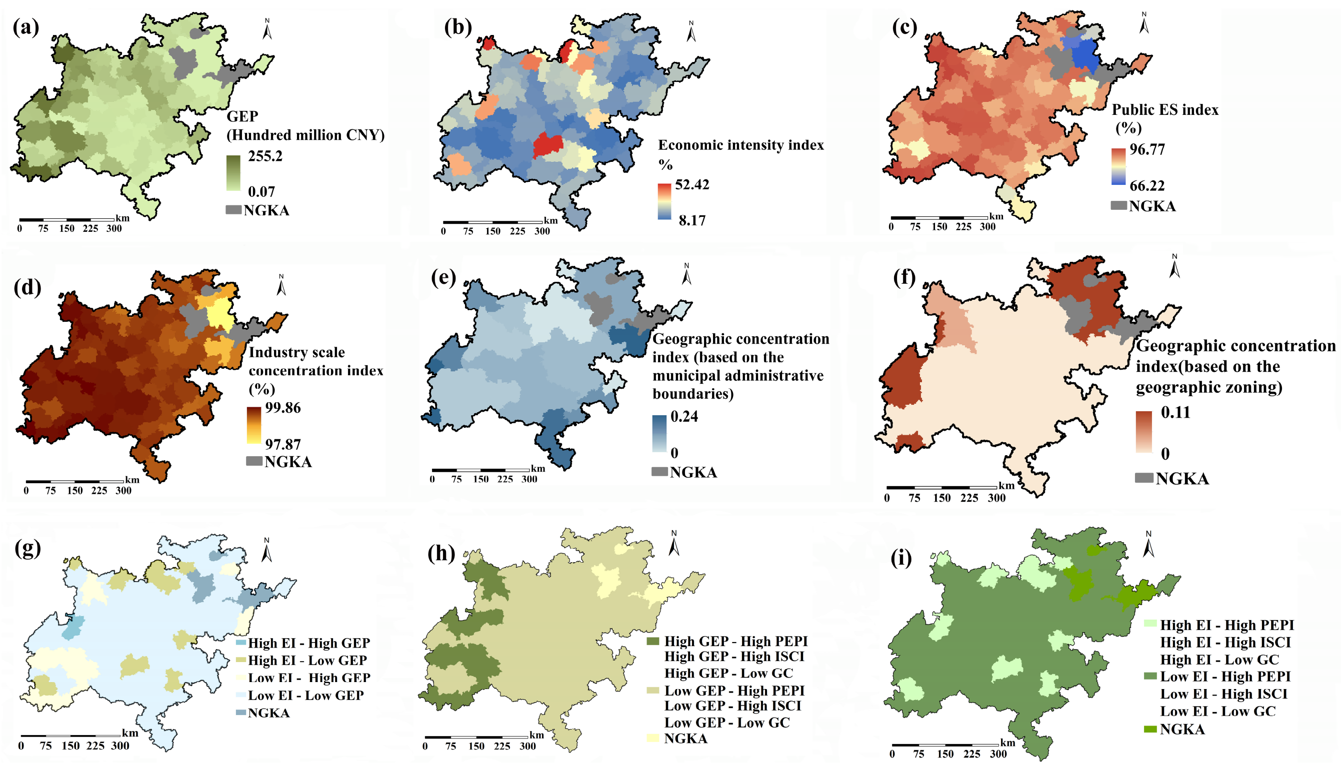

Figure 4. Spatial distribution of grassland GEP in the KDC and its characteristics (NGKA: no grassland in the karst area, EI: economic intensity, PEPI: public eco-product index, ISCI: industrial scale concentration index, and GC: geographical concentration; (**a**), Distribution of GEP; (**b**), Distribution of EI; (**c**), Distribution of public ES index; (**d**), Distribution of ISCI; (**e**), Distribution of GC (based on the municipal administrative boundaries); (**f**), Distribution of GC index (based on the geographic zoning); (**g**), Spatial coupling of GEP and EI; (**h**), Spatial coupling between GEP and PEPI, ISCI, GC; (**i**), Spatial coupling between EI and PEPI, ISCI, GC).

Table 3. Indicators analysis of grassland GEP in the KDC.

Indicators	Mean	Variation Range	Median	Skewness	Kurtosis
GEP (0.1 billion CNY)	58.12	255.13	39.84	1.58	2.37
County economic intensity (%)	20.74	44.24	18.49	1.58	2.64
Public eco-product index (%)	89.83	30.55	90.86	−2.36	7.32
Industrial scale concentration index (%)	99.48	1.99	99.56	−2.73	10.03
Geographical concentration (based on the municipal administrative boundaries)	0.069	0.24	0.06	1.41	1.56
Geographical concentration (based on the geographic zoning)	0.037	0.11	0.03	2.68	0.81

In 2020, the counties' economic intensity in the study area ranged from 8% to 53% (Figure 4b). The distribution is highly positively skewed and has low kurtosis. Among them, the majority of counties have an economic intensity below 30% (Table 3). Counties with strong economies are distributed in a dotted pattern, mostly counties where municipal administrative districts are located, such as Zhongshan District (52.41%), Youjiang District (51.45%), Xixiu District (43.65%), etc., or in areas closer to provincial capitals, such as Longli County (52.42%). Economically underdeveloped regions are mainly located in the southwest, southeast, and northeast of the study area, such as Guangnan County (8.18%), Du'an County (8.2%), Congjiang County (9.33%), etc. In general, it basically forms a distribution status quo with the municipal administrative center as the radiance, and the farther from the administrative center, the less economically developed.

The median line was used as the basis for classification, and the economic intensity of the counties and the GEP of grassland in the KDC were divided into four combination types. Among the 86 counties, there are 64 counties with low economic intensity—low GEP and 10 counties with low economic intensity—high GEP, accounting for 74.42% and 11.63% of the total number of counties, respectively. These two types of counties account for 86.05% of the total number of counties. There are 11 counties with high economic intensity—low GEP and 1 county with high economic intensity—high GEP, representing 12.79% and 1.16% of the total number of counties, respectively (Figure 5). Spatially, counties with low economic and low intensity GEP are widely distributed, and other types of counties are distributed at the edge of the study area (Figure 4g).

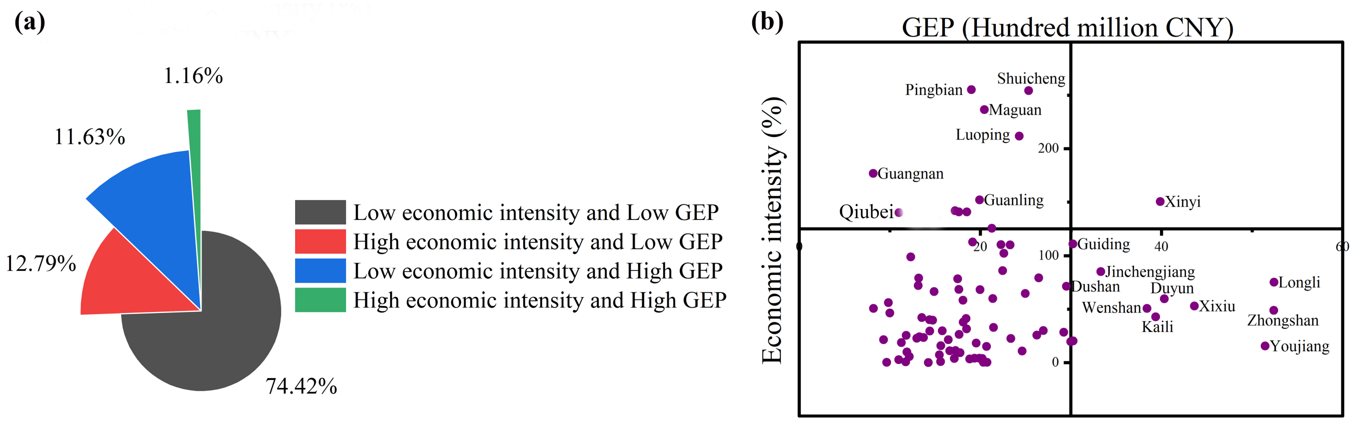

Figure 5. Spatial coupling relationship between the GEP of grassland and county economic intensity in the KDC (**a**), Structural distribution of different types of GEP and county economic intensity combinations; (**b**), Spatial distribution of different combinations of GEP and county economic intensity).

Based on the perspective of spatial autocorrelation, the Moran indices of GEP and economic intensity of stone desertification management grasslands were 0.46 and 0.129, respectively, indicating that there was a spatial aggregation effect. The hotspot area of GEP was the western part of the study area, and the hotspot area of economic intensity was distributed in a point pattern. The GEP and economic intensity were spatially misaligned (Figure 6). It can be seen that the grassland ES in the KDC mainly comes from areas with lower economic intensity, and this distribution pattern is basically consistent with the theoretical hypothesis of Figure 1a.

3.2. Structural Characteristics of Grassland GEP in the KDC

The public ES index of grassland in the KDC of the study area ranges from 66.22% to 96.77% (Figure 4c), with a negatively skewed and low kurtosis distribution (Table 3), and most counties (88.37%) above 85% (Figure 7a). It supports the scientific conjecture of Figure 1b. Overall, there was little variation between counties. Spatially, counties with a high public eco-product index are relatively concentrated, while counties with a relatively low index are mainly found in the outlying areas of the study area. Counties with a relatively low index include Jinping County (66.22%), Liping County (69.51%) and Jianhe County (71.99%), etc. Counties with a high index include Pingbian Miao Autonomous County (96.77%), Qinglong County (95.93%), and Shuicheng District (95.88%), etc.

In terms of the index of industry scale concentration of grassland GEP in the KDC, all counties in the study area were consistently above 97% (Figure 4d), with a negatively skewed, low kurtosis distribution (Table 3). In addition, most counties (94.19%) were above 99% (Figure 7b). The reason is that the value among GEP components is mainly concentrated in five ES: soil retention, material goods, climate regulation, carbon sequestration, and oxygen release. Among the five ES with the largest value, the largest proportion is accounted for by ecological regulation services (63.73–96.79%) and a smaller proportion is accounted for by provisioning services (3.21–34.27%).

In terms of the distribution of the industrial structure of grassland ES with GEP and county economic intensity in the KDC, the study area basically formed a distribution trend of high public eco-product index, low GEP, and low economic intensity (Figure 4h,i). Counties with a high public ES index and high GEP were mainly distributed in the western part of the study area, such as Pingbian Miao autonomous county, Qubei county, and Shuicheng district. The counties with a high publicness ecological product index and high economic intensity are distributed in a dotted pattern, which is basically consistent with the spatial distribution of high economic intensity.

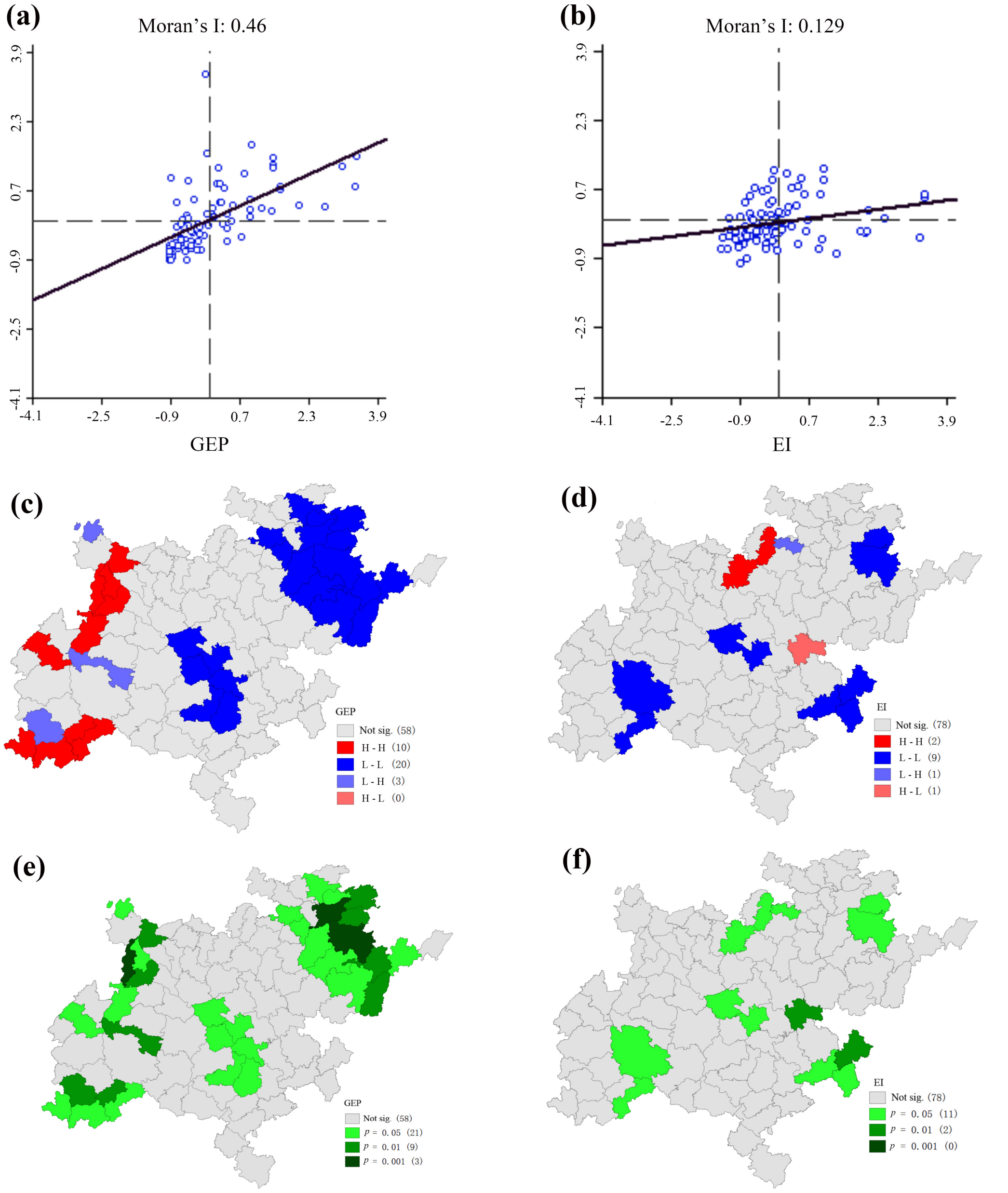

Figure 6. Moran index of GEP and economic intensity in the study area. (**a**) Moran index of GEP in the KDC; (**b**) Moran index of economic intensity; (**c**) Spatial autocorrelation distribution of GEP; (**d**) Spatial autocorrelation distribution of economic intensity; (**e**) Spatial autocorrelation significance of GEP; and (**f**) Spatial autocorrelation significance of economic intensity. EI: economic intensity; Not sig.: Not significant; H-H: High-High; L-L: Low-Low; L-H: Low-High; and H-L: High-Low.

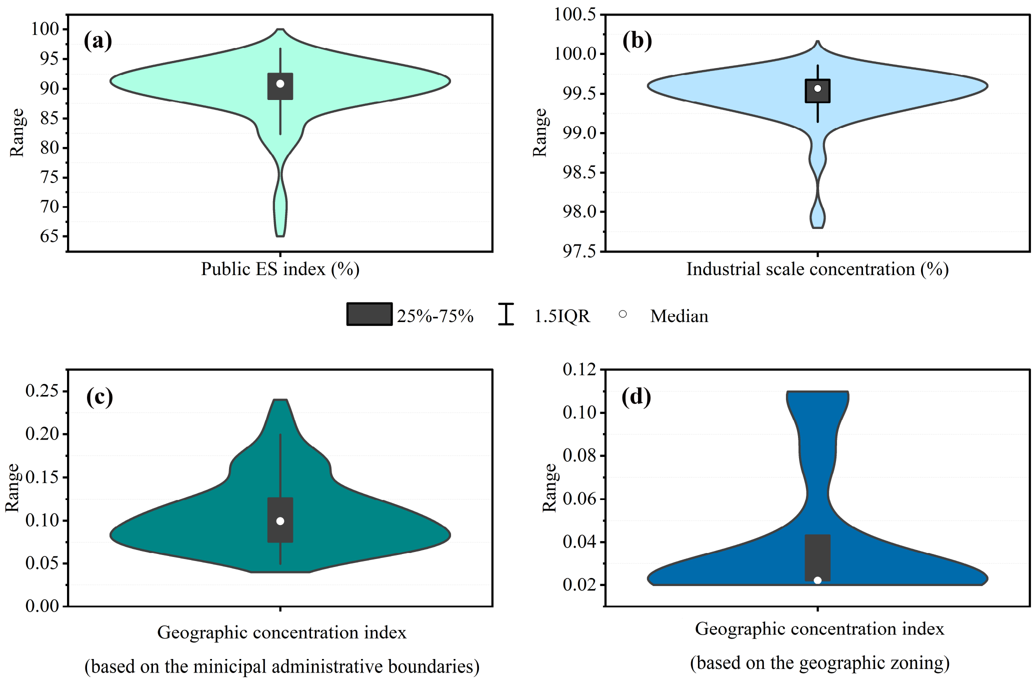

Figure 7. Structural and spatial characteristics of grassland ES in the KDC.

3.3. Spatial Characteristics of Grassland GEP in the KDC

The geographic concentration of grassland GEP in the KDC of the study area is generally low, with a positively skewed, low kurtosis distribution (Table 3). Based on the municipal administrative boundaries, the geographical concentration ranges from 0.015 to 0.237. Among them, Liuzhou city (0.237), Honghe Hani and Yi Autonomous Prefecture (0.178), and Chongzuo City (0.11) are relatively higher, and Wenshan Zhuang and Miao Autonomous Prefecture (0.042), Qianxinan Buyi and Miao Autonomous Prefecture (0.037), and Qiannan Buyi and Miao Autonomous Prefecture (0.015) are lower. The overall trend is decreasing from the periphery to the center (Figure 4e). Based on geomorphological zoning, the geographic concentration of grassland ES in the KDC of the study area ranges from 0.022 to 0.108, with karst trough valley (0.108) > karst faulted basin (0.079) > karst gorge (0.043) > karst plateau (0.024) > karst peak cluster depression (0.022) (Figure 4f). The small geographical concentration of grassland ES in the KDC verifies its significant spatial variability and unevenness (Figure 7c,d). This leads to a low scale of grassland eco-industry, which conforms to the theoretical hypothesis of Figure 1c.

In terms of the relationship between the industrial geographic of grassland ES in the KDC and the GEP and the counties' economic intensity, the distribution pattern is consistent with the results of Section 3.2 (Figure 4h,i). Therefore, in a comprehensive view, the grassland ES in the KDC have typical industrial characteristics of low economic intensity, low GEP, high public ES index, and low geographic concentration, which increased the complexity, difficult, and long-term nature of transforming the economic benefits.

4. Discussion

Scientifically measuring the value of nature to people [49] and incorporating ES and natural capital into mainstream economic policy is an important step toward improving ES and human well-being [50–52]. However, this presupposes an understanding of the three elements of an ES. The first is physical quantity and value quantity from ES to nature's contribution (including positive and negative) to people [53]. Second, according to the classification of ES [54], the structural proportions of ES value should be considered, and the feasibility of private market-based transactions should be clarified. Finally, the spatial patterns of an ES should be fully considered. In particular, the flow and enhancement pathways from an ES to ecological capital and human well-being should be explored in the context of local socioeconomic systems [55,56]. Accordingly, focusing on karst desertification areas, we should use the typical characteristics of the grassland GEP in the KDC to inform economic decisions for achieving inclusive and sustainable development by managing ES (Figure 8).

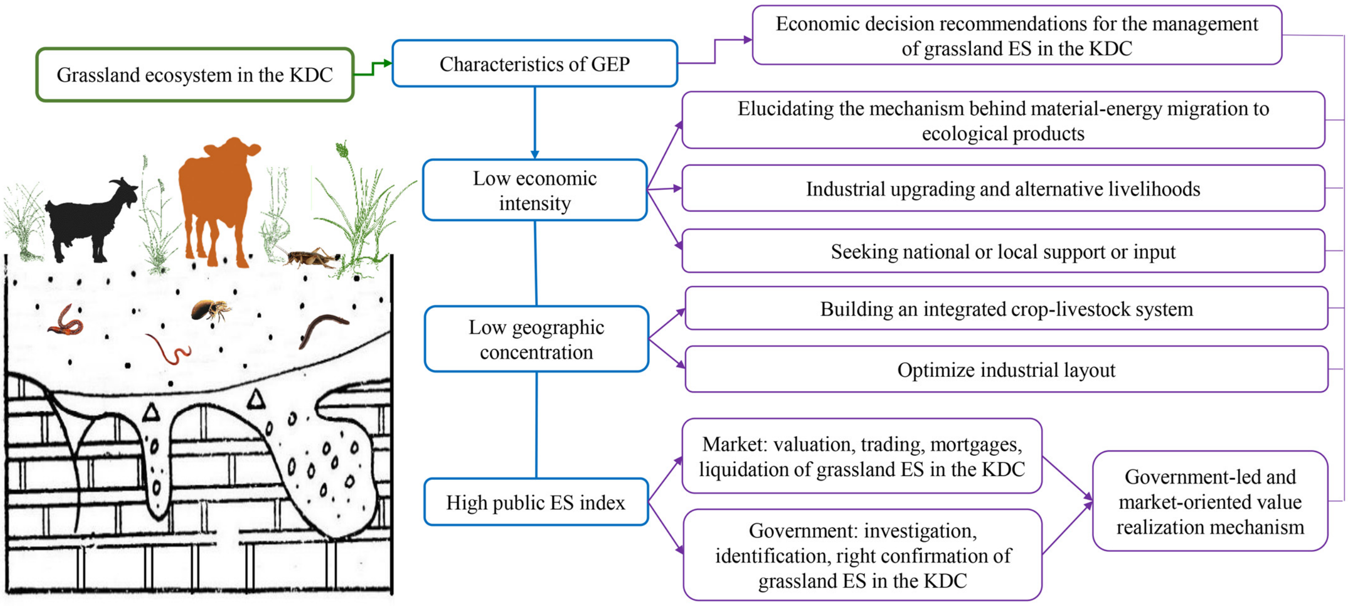

Figure 8. Recommendations for the management of the grassland ES in the KDC.

4.1. Spatial Coupling Relationship between Grassland GEP in the KDC and County Economic Intensity

Grassland GEP in the KDC mainly come from rural and remote areas with relatively less developed economies and traditional industries. At the same time, the region has a background of high population pressure [57]. Farmers and herders are prone to over-grazing based on their livelihood needs. Moreover, grasslands tend to develop into arable lands [58]. This leads to the destruction and degradation of grasslands, which in turn affects the provision of ESs, resulting in the loss of natural capital. This feature is consistent with the arid and semi-arid temperate steppes and alpine grasslands of Xinjiang, Inner Mongolia, China, Central Asia region [59–62]. However, it is different from the economically developed ranches of Western Europe, the Central Great Plains of the United States, Australia, and the Pampas of Latin America. This corroborates the findings of Ganguli and O′Rourke [63].

Due to this, it is essential to improve the quality and efficiency of the grassland ES in the KDC and to seek alternative livelihoods for farmers. Since most of the grassland patches in the KDC are located in economically underdeveloped remote rural areas, coupled with large populations and high livelihood pressures [64], the survival and development of farmers is an inevitable reality. After decades of KDC and socioeconomic development, the current main contradiction in the region has changed to the gap between the supply of quality eco-products and human needs for a beautiful ecological environment. Therefore, we should elucidate the migration mechanism of rock, soil, water, and gas elements to animals and plants in karst grasslands with different terrains, lithologies, climates, grades of karst desertification, and social ecosystems in order to provide theoretical support for improving the supply capacity of high-quality ES. Furthermore, we should develop derivative industries, extend the ecological industrial chain through industrial integration and development, and increase the value added of ecological products. Accordingly, we should also promote labor migration and flexible employment to increase the income of farmers and herders. Equally important, it is critical to seek national or local policy and financial support in agriculture, science and technology, the environment, poverty alleviation, etc., to enhance the endogenous driving force for development.

4.2. Industrial Spatial Characteristics of Grassland GEP in the KDC

Grassland in the KDC is an ecosystem controlled by special geological conditions (e.g., carbonate rocks) [65]. The complex and unique hydrogeological structure results in an extremely fragile ecological environment [66]. Due to the control of karst degradation ecosystem structure, function, and process [67], grasslands in the KDC show fragmented, small, and scattered spatial patterns with significant non-equilibrium and heterogeneous characteristics in space [68,69]. This is a distinctive feature that distinguishes the grasslands in the KDC from other grassland ecosystems, such as tropical and subtropical savannas, temperate steppes, and arctic-alpine grasslands with concentrated and cohesive features in Eurasia (e.g., Himalayas of South Asia and China, Afghanistan—Xinjiang—Inner Mongolia, China, five Central Asian countries, and Russia), South America, and East Africa.

Influenced by the low spatial concentration of grassland GEP in the KDC, the costs of industrial development are high, and the benefits of economies of scale are low. However, the region has a dominant agroecosystem and is rich in biological resources [70,71]. Still, from November to February, much of the arable land is available for grazing or forage production. Moreover, refined agricultural management (e.g., weed mowing) can provide sufficient forage resources for livestock development within the context of population benefits, and the potential of converting grain to forage can compensate for the lack of grassland resources in karst areas. Thus, by optimizing the structure of grass resources, cereals, warp, and forage crops, we can increase feed sources and ensure feed supply. Moreover, a reasonable industrial layout can be designed by developing and using local resources (e.g., flora, fauna, climate, and land), with the market playing a crucial role in resource allocation.

4.3. Structural Characteristics of the Grassland GEP in the KDC

Publicity and externality are the distinctive features of grassland GEP in the KDC. The value of regulating services of grassland ES in the KDC accounts for more than 60% of the GEP, which is largely consistent with the structural characteristics of ES values such as forests and wetlands, etc., [72,73]. Due to the typical public and external characteristics of GEP, most grassland GEPs in the KDC have the dilemma of being difficult to define, quantify, trade, and transfer [74,75]. On the one hand, the non-competitive and non-exclusive characteristics of grasslands in the KDC have led to market failures. Due to the "tragedy of the commons", the stakeholders of grassland in the KDC area cannot achieve the appropriate returns, and their enthusiasm is inhibited. On the other hand, since any active subject can possess more resources without paying or at a lower cost, economic behavior evolves in the direction of over-cultivation of grasslands, overgrazing, and random emissions, which leads to the destruction of resources and the environment, thus threatening the livelihood of farmers and herders. It can be seen that the publicness and externalities of grassland GEPs in the KDC are important shortcomings that restrict the improvement of ES and human well-being, as well as the public issues facing non-karst grasslands globally. This issue is not only unique to grasslands in the KDC, but also to non-karst grasslands and other terrestrial ecosystems.

Despite the dilemma that the ES value of grasslands in the KDC is difficult to transform through the market, it is also important to recognize the potential of transforming public ES into economic benefits. Public ES are a difficult and painful point of value realization and have the potential to be explored to improve the value realization rate of ES. This needs to be supported by the application of two extremely important instruments: government and market [76,77]. On the one hand, it may be most effective to integrate the management of ES into the existing government policy framework [78]. At the same time, a public ES requires the government to be the largest provider and consumer [79]. It is equally important for the government to fully play its management role and strengthen its services in identifying and managing resources of a public nature to create the conditions for ecosystem goods and services to enter the market. On the other hand, the market is an important lever in regulating the supply and demand of ES [80]. The crucial role of the market in resource allocation should be fully realized to achieve the goal that ES providers receive benefits and consumers pay. It is highlighted that governments and markets are not two instruments used independently but are mutually supportive and complementary [81]. The absence of either instrument can lead to a significant reduction in the realization rate of the ES value. For this reason, it is necessary to create a government-led and market-oriented mechanism to improve the value realization rate of grassland ES in the KDC.

5. Conclusions

In this paper, the contiguous area of karst desertification in Yunnan-Guangxi-Guizhou, China, were taken as the study area, and the GEP of grassland in the KDC and the economic intensity of counties were calculated. At the same time, we analyzed the structural and spatial characteristics of grassland GEP in the KDC using geospatial analysis methods, and based on this, the corresponding economic decision proposals are put forward. We found that the GEP of grasslands in the KDC is unevenly distributed, mainly in the areas with low economic intensity of counties. The socio-ecological system of grasslands in KDC is similar to that of temperate grasslands in northern China and Central Asia and alpine meadows in the Qinghai-Tibet Plateau, but different from that of economically developed pastures in European countries, the United States, Australia, and Argentina. Meanwhile, due to the small and scattered landscape pattern, the geographical concentration of grassland in the KDC is low (0.015–0.237). It is difficult to expand the industrial scale and form industrial advantages. This characteristic differs from the globally concentrated and continuous grasslands in non-karst areas. In addition, the high index of public ES (66.22–96.77%) of grasslands in the KDC is basically consistent with the distribution trend of service values of major ecosystems globally and faces the dilemma of difficult transformation of market economic benefits. According to the structural and spatial characteristics of grassland GEP in the KDC, we should elucidate the mechanism behind material–energy migration to ecological products, develop an integrated crop–livestock system, seek alternative livelihoods, and use both government and market instruments to promote the monetary value transformation of public ES.

Focusing on the contiguous region of karst desertification in Yunnan-Guangxi-Guizhou, China, we point out the current shortcomings of improving grassland ES and enhancing human well-being in the KDC by analyzing the characteristics of GEP. Accordingly, we propose a two-pronged strategy recommendation. In contrast to previous physical and spatial analyses that focused on ecological attributes, we considered not only the economic value of nature to people, but also economic intensity and spatial patterns. This makes our recommendations more targeted and operational. The research results can provide theoretical support to inform economic decisions for ecosystem protection and restoration, value realization of ecosystem products, urban–rural integration development, and rural revitalization in the KDC areas with similar man–earth areal systems (e.g., Southeast Qinghai-Tibet Plateau—Southwest China—South Central Peninsula region) or even other ecologically fragile areas around the world.

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Abbreviations

ES	Ecosystem services
KDC	Karst desertification control
GEP	gross ecosystem product
NGKA	no grassland in the karst area
EI	economic intensity
PEPI	public eco-product index
ISCI	industrial scale concentration index
GC	geographical concentration

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