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Landscape Character Identification and Zoning Management in Disaster-Prone Mountainous Areas: A Case Study of Mentougou District, Beijing

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Abstract: Disaster-prone mountainous regions face complex human–environment conflicts resulting from the combined influences of natural disaster threats, ecosystem conservation, and resource development. This study takes Mentougou District as the research area, leveraging landscape character identification methods to develop a multidimensional evaluation framework integrating safety, ecology, and landscape aspects, providing a foundation for zoning and management decisions. Four characteristic elements—elevation, geomorphology, vegetation type, and land cover type—were extracted during the landscape character identification phase. Two-step clustering and eCognition multi-scale segmentation were used to identify 12 landscape character types (LCTs) and delineate Landscape Character Areas (LCAs). The MaxEnt model was applied during the evaluation phase to assess debris flow susceptibility. At the same time, AHP and ArcGIS spatial overlay methods were used to evaluate ecological resilience and landscape resource quality. The three-dimensional evaluation results for the 12 LCAs were clustered and manually interpreted, resulting in four levels of protection and development areas. Management strategies were proposed from three perspectives: debris flow disaster prevention, ecosystem conservation, and landscape resource development. This method provides a pathway to balance human–environment conflicts in disaster-prone mountainous regions, promoting scientific zoning management and sustainable development in vast mountainous areas.

Keywords: landscape character identification; mountainous regions; natural disasters; human–environment conflicts; zoning management

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1. Introduction

Mountain regions cover 22% of the global land surface, functioning as crucial reservoirs of essential resources and primary hubs for recreation [1]. Mountain ecosystems are indispensable for sustaining the balance and survival of global ecological networks. China has the widest mountain distribution globally, with mountains covering 69% of its territory. Nearly one-third of its population resides in mountainous areas, where half of the country's towns originate and grow, showcasing distinct mountainous traits [2,3]. Compared to plain cities, mountainous regions in China exhibit intricate geological and ecological conditions, with land use patterns and distributions more heavily dictated by environmental constraints [4]. The synergy of intricate geological formations and distinctive topographical features results in abrupt shifts in atmospheric, soil, vegetation, and hydrological conditions over short spans [5–7], generating fragile habitats and predisposing areas to mountain hazards such as debris flows, rockfalls, and landslides [8]. Such dynamics intensify regional disparities, keeping the economic growth of mountain towns consistently below the national average [9,10]. Throughout history, the dynamic interplay between local communities and unique natural settings has fostered a rich repository of historical and cultural heritage and natural landscapes, holding immense potential for cultural tourism development and regional economic revitalization [11]. However, suitable land for

construction is limited in mountainous regions, requiring modifications to the terrain to secure space for development [12]. The fragmented settlements and challenging terrain of mountainous regions hinder integrated management, often resulting in uncontrolled growth and illegal land acquisition. These practices elevate disaster risks while eroding intrinsic landscape features and significantly disrupting the diversity and coherence of mountain landscapes [13]. Thus, reconciling development objectives with ecological integrity through prudent zoning and planning has emerged as a critical challenge to the sustainable progress of mountain regions.

To address the low-quality development of mountainous landscapes caused by inadequate systematic planning, researchers must identify the existing regional landscape characteristics and evaluate the associated pressures and opportunities [14]. These landscape characteristics, which emerge from the dynamic interplay between natural and anthropogenic factors, are represented by distinct, recognizable, coherent combinations of elements that differentiate landscapes [15]. Through integration, these landscape characteristics shape continuous Landscape Character Areas (LCAs), highlighting the coherence and interconnectedness of natural geography and ecosystems and acting as fundamental landscape planning and governance units [16]. LCAs delineate the authentic boundaries of landscapes, enabling the extraction of structural and compositional elements within a region, which supports the evaluation of landscape conditions and degrees of disturbance [17]. Researchers have applied landscape character identification across various scales to facilitate regional spatial and administrative cohesion [18,19] while developing classification methods tailored to national parks to improve zoning management [20]. Identifying and evaluating LCAs are widely employed in zoning planning, striking a balance between preserving landscape characteristics and formulating strategic regional development guidance. In terms of evaluation systems, researchers not only focus on landscapes' perceptual attributes and values but also extend their research to related fields that encompass their diverse attributes—for example, merging LCAs with cultural ecosystem services evaluations [21]. Within recreation-focused studies, researchers have performed visual sensitivity evaluations [22] and greenway routing analyses [23] using LCAs, thereby crafting recreational spatial structures. Additionally, researchers have developed evaluation models targeting landscape health [24] and metropolitan landscape sensitivity [16], providing recommendations for zoning and management of LCAs. Based on landscape character identification frameworks, these studies provide theoretical foundations for developing and sustainable using landscape resources across diverse perspectives.

Current evaluation systems predominantly emphasize landscapes' intrinsic attributes, seldom incorporating interdisciplinary perspectives to establish comprehensive multidimensional frameworks. Achieving a balance between "development" and "safety" in mountainous landscape planning requires addressing three key issues: (1) reducing losses from natural disasters, (2) enhancing ecological resilience, and (3) utilizing resources for rational development and construction.

Mentougou District is the only entirely mountainous district among Beijing's 16 districts. It boasts abundant natural resources and historical and cultural heritage, which are vital to safeguarding Beijing's ecological security barrier [25]. Early activities such as mining and logging caused significant damage to the mountainous environment [26]. With Beijing's industrial restructuring, Mentougou District is transitioning from a traditional mining-based economy to modern service industries, but it also faces pressures from rapid urbanization and natural disasters. As a predominantly mountainous region, most villages and towns in Mentougou are located on gently sloping alluvial fans prone to debris flows [27], leading to multiple catastrophic events. The lack of strict and orderly guidance and regulation in development and construction has resulted in severe damage from debris flow disasters, significantly hindering the sustainable development of Mentougou District.

This study aims to establish an integrated evaluation framework for LCAs in disaster-prone mountainous regions. By incorporating geological disaster prediction methods, the study focuses on typical regional disaster risks and proposes a multidimensional evaluation

system addressing safety, ecology, and landscape in disaster-prone mountainous areas. The dimension of safety addresses susceptibility to debris flow disasters; the ecological aspect evaluates the adaptability and recovery capacity of ecosystems under human-induced disturbances; and the landscape dimension examines the quality and potential of natural and cultural landscape resource development within the region. The study utilizes this evaluation framework to examine the interplay among debris flow susceptibility, ecological resilience, and landscape resource quality across various LCAs, proposing zoning strategies and management recommendations. Based on regional ecological safety, the proposed methodology creates an improved and comprehensive evaluation framework that promotes the development of accurate and unbiased zoning management strategies to resolve human–environment conflicts in mountainous areas.

2. Materials and Methods

2.1. Research Area

Mentougou District is located southwest of Beijing (115°250 E–116°100 E longitude, 39°480 N–40°100 N latitude) and covers a total area of 1447.85 km^2 (Figure 1). The topography ascends in the northwest and descends in the southeast, with mountains comprising 98.5% of the district and plains accounting for the remaining 1.5%. The district receives an average annual precipitation of approximately 576.02 mm [28], with precipitation unevenly distributed across time and space due to the complex terrain. Coupled with its complex geological structure and extensively weathered rocks, the region is highly susceptible to debris flow during heavy rainfall [27], ranking as one of the most geologically disaster-prone and severely affected areas in Beijing. Debris flow incidents have significantly damaged residents' lives, assets, tourism facilities, and vegetative landscapes. With a forest coverage rate of 48.08% and the Yongding River meandering through its expanse, Mentougou District stands as a critical ecological shield and water source conservation zone for Beijing. Furthermore, the convergence of the Western Hills–Yongding River and Great Wall cultural belts and numerous historic villages nestled in its valleys solidifies Mentougou District's rich historical and cultural deposits.

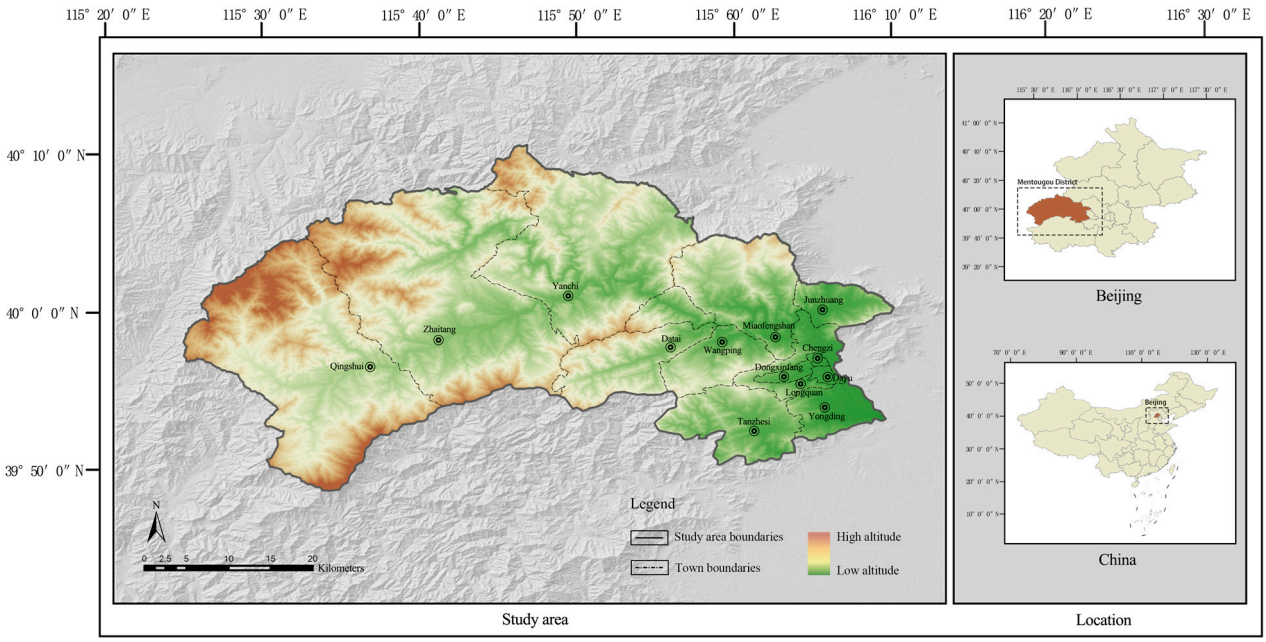


Figure 1. Location of the Mentougou District.

2.2. Methodology

The methodology employed in this study comprises three primary components (Figure 2): (1) Identification and classification of LCAs to minimize the impact of ad-

ministrative boundaries, thereby delineating independent landscape boundaries and their characteristics. (2) Guided by the safety–ecology–landscape multidimensional evaluation framework, evaluations of debris flow susceptibility, ecological resilience, and the quality of landscape resources for each LCA will be conducted to achieve a holistic understanding of each area. (3) Synthesizing the results from the three evaluation dimensions to categorize areas into development and conservation levels, accompanied by tailored development suggestions.

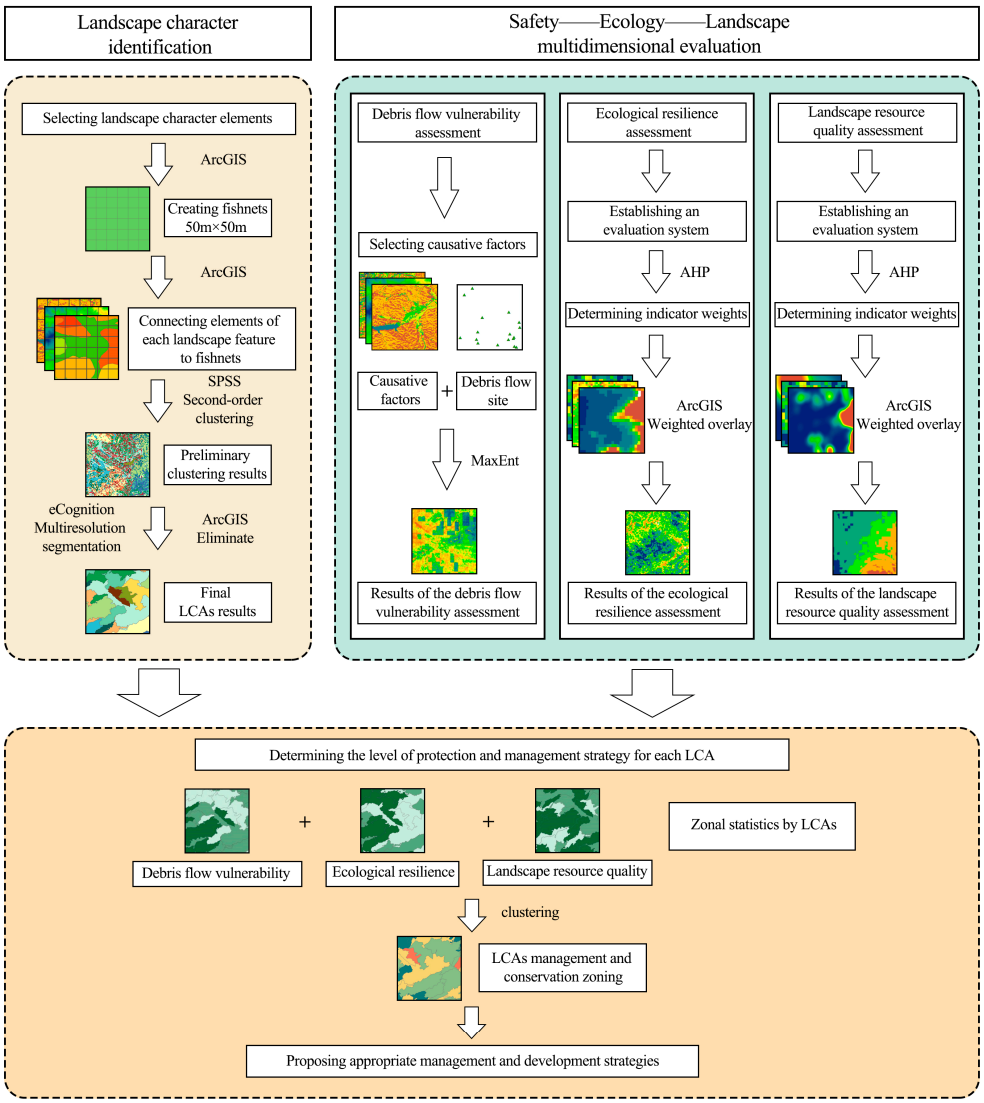


Figure 2. Methodological framework.

2.2.1. Landscape Character Identification

Drawing on the European Landscape Character Assessment initiatives and relevant studies [29–31], different research scales necessitate using varying elements to delineate landscape characteristics. Based on the size of the Mentougou District, this study identifies the research scale as regional. Considering the complexity of mountainous terrain and geomorphology, natural vegetation types vary significantly with elevation. Additionally, land cover types reflect the extent and intensity of human development in the natural environment. Four key elements—elevation, geomorphology, vegetation type, and land cover—were selected and encoded to analyze these factors, as detailed in Table 1. All landscape characteristic data were standardized to a unified coordinate system and resolution, resampled into 50 m*50 m grid units, producing 146,233 landscape samples, with

the data attributes assigned to each grid unit. Data from each grid cell were extracted and processed using SPSS27 for standardization and principal component analysis to mitigate dimensional influences and guarantee variable independence [32]. Due to its high reliability, the two-step clustering algorithm offers advantages in processing large datasets and automatically determining cluster numbers [33], frequently employed in landscape character identification at both regional and local scales. Accordingly, SPSS27's two-step clustering was used to synthesize the four groups of landscape characteristic data. After evaluating clustering quality for various predefined cluster numbers, 15 landscape types were finalized with high clustering quality. Cluster IDs were assigned to grid units for visualization, generating an initial distribution map of landscape character types (LCTs).

Table 1. Landscape character elements selected for the research area.

Landscape Character Elements		Classification	Code	Data Source
Topography	Altitude	Low-altitude	A1	30 m × 30 m resolution DEM (http://srtm.csi.cgiar.org) accessed on 14 September 2024
		Mid-altitude	A2	
		High-altitude	A3	
	Landform	Plain	U1	30 m × 30 m resolution DEM (http://srtm.csi.cgiar.org) accessed on 14 September 2024
		Terrace	U2	
		Gently undulating hills	U3	
		Moderately undulating hills	U4	
		Moderately undulating mountains	U5	
		Steeply undulating mountains	U6	
Vegetation type		One year one ripe grain fields and cold-tolerant economic crop fields	V1	1:1,000,000 Atlas of Chinese Vegetation
		Temperate tufted low grass, nano-semi-shrub desert steppes	V2	
		Temperate tufted grass steppes	V3	
		Deciduous scrubs in temperate zone	V4	
		Temperate deciduous broad-leaved forest	V5	
		Temperate deciduous coniferous forest	V6	
Type of land cover		Grassland	L1	2022 10 m × 10 m European Space Agency land cover (https://esa-worldcover.org/en) accessed on 14 September 2024
		Shrubland	L2	
		Tree cover	L3	
		Cropland	L4	
		Built-up	L5	
		Permanent water bodies	L6	

The fragmented and scattered nature of the identified LCAs limited their capacity to represent cohesive spatial distribution patterns. Smaller patches frequently maintained continuity with adjacent landscape matrices [34], necessitating integrated analysis. eCognition was employed for multi-resolution segmentation of satellite imagery to delineate more integrated natural element boundaries, serving as a reference for LCAs delineation. eCognition typically segments images into multi-pixel objects of varying sizes [35], with broad applicability at both regional and national scales. After iterative adjustments of environmental variables and comparative analyses, the optimal parameters for scale, shape, and compactness were determined to be 500, 0.1, and 0.5, achieving segmentation results that were consistent with the study's objectives. Preliminary LCTs were converted into sample points, classified through eCognition's "classified image objects to samples", and categorized segmentation results were imported into ArcGIS. Lastly, We used elimination tools to denoise the data, removing small landscape character patches that differed significantly from their surroundings, yielding the Mentougou District LCAs map. Representative features for each LCT were identified and synthesized into composite names.

2.2.2. Assessment of Susceptibility to Debris Flow

The evaluation of debris flow susceptibility entails identifying critical environmental factors that trigger debris flows in the study area, followed by a comprehensive analysis to estimate the probability of occurrence in particular regions. Modern machine learning techniques excel in processing extensive disaster points and evaluation variables datasets, leveraging autonomous learning to yield highly accurate predictive outcomes. The MaxEnt model, a presence-only model learning approach devised by S.J. Phillips and colleagues in 2004, was initially utilized to model the spatial distribution of species [36]. Recently, it has been extensively used to simulate the susceptibility of debris flows [37], landslides [38], and other disaster events. MaxEnt operates on the principle that, out of all potential probabilistic models, the one with maximum entropy is considered ideal [39]. If the probability distribution of a discrete random variable x is represented as P(x), its entropy can be defined as:

$$H(P) = -\sum_{x} P(x)\log P(x)$$

The MaxEnt model was employed in this study to evaluate debris flow susceptibility. Locations of prior debris flow incidents were saved as CSV files containing latitude and longitude information as dependent variables. In contrast, disaster-inducing indicators were formatted as ASC files for use as independent variables. Ten environmental indicators influencing disasters were selected: Normalized Difference Vegetation Index (NDVI), soil type, elevation, slope, lithology of bedrock, fault density, proximity to rivers, proximity to roads, population density, and mean annual precipitation [40–42], refer to Table 2. The importance of the indicator was validated using the jackknife technique. The model's effectiveness was assessed using the area under the receiver operating characteristic curve (AUC). The model results indicate that the average training set AUC value from 10 cross-validations for debris flow-prone areas in the study region was 0.896, exceeding the AUC value of the random distribution (0.500). This demonstrates the model's high accuracy in simulating debris flow susceptibility.

Table 2. Debris flow susceptibility assessment indicators and their sources.

Indicator	Data Source
spatial distribution of debris flow points	2023 Spatial distribution data of geological hazard points (https://www.resdc.cn/data.aspx?DATAID=290) accessed on 3 October 2024
normalized difference vegetation index	2022 30-m resolution annual maximum NDVI raster data in China [43] (http://www.nesdc.org.cn/sdo/detail?id=60f68d757e28174f0e7d8d49) accessed on 3 October 2024
population density	2020 100 m × 100 m Population Density Data from Worldpop (https://www.worldpop.org/) accessed on 3 October 2024
soil type	China Soil Database [44]
distance from road	Urban road network from Open Street map
distance from river	2022 10 m × 10 m European Space Agency land cover (https://esa-worldcover.org/en) accessed on 3 October 2024
elevation	30 m × 30 m resolution DEM (http://srtm.csi.cgiar.org/srtmdata/) accessed on 3 October 2024
slope	30 m × 30 m resolution DEM (http://srtm.csi.cgiar.org/srtmdata/) accessed on 3 October 2024
bedrock lithology	1:2,500,000 Geological Map (https://geocloud.cgs.gov.cn/geological/) accessed on 3 October 2024
fracture zone density	1:2,500,000 Geological Map (https://geocloud.cgs.gov.cn/geological/) accessed on 3 October 2024
average annual rainfall	2022 The ERA5-Land dataset released by organizations such as the European Union and the European Centre for Medium-Range Weather Forecasts (ECMWF) (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land-monthly-means?tab=overview) accessed on 15 December 2024

2.2.3. Ecological Resilience Assessment

An ecosystem (ES) is a complex adaptive system capable of creating new ecological states through adaptation to external changes [45]. Ecological resilience is defined as the capacity of a system to withstand disruptions caused by anthropogenic and natural factors while retaining and reorganizing its intrinsic ecological attributes (including functions, structures, and feedback) [46]. Numerous models for assessing ecological resilience have been developed, focusing on quantifying ecosystem pressures, service capacities and biodiversity. This study focuses on the recovery potential of ecosystems influenced by anthropogenic disturbances and identifies human activities, habitat quality, and biodiversity as primary evaluation indicators. Due to pronounced human–environment conflicts, unregulated development and construction have disrupted natural landscapes and exacerbated losses from debris flow disasters, significantly impacting regional sustainable development. Accordingly, nighttime light intensity, road density, and proximity to built-up areas were chosen as secondary indicators under the human activity indicator. Moreover, vegetation, covering over 90% of the region, constitutes a cornerstone of the ecosystem, with its quality profoundly affecting ecological stability and health. Thus, NDVI and net primary productivity (NPP), which directly reflect vegetation growth and productivity, were used as indicators of habitat quality. Regarding biodiversity, landscape patch diversity determines species richness, while connectivity supports population stability through enhanced species migration and genetic exchange. Accordingly, Fragstats was employed to compute Shannon's diversity and connectivity indices, serving as secondary biodiversity indicators. A moving window approach was utilized, optimizing the window radius to 250 m to establish the ideal scale for landscape pattern analysis in the Mentougou District. To summarize, a framework of seven indicators was constructed to assess ecological resilience in the region, refer to Table 3. Using the Analytic Hierarchy Process (AHP), a judgment matrix was created from 10 expert surveys in relevant fields, and consistency testing was applied to establish indicator weights. A range normalization approach was adopted for dimensional adjustment to facilitate comparability among indicators with varying scales. Indicators were classified as positive or negative based on their implications, and the calculation formulas are provided below.

$$Y_{ij} = \frac{X_{ij} - \min(X_j)}{\max(X_j) - \min(X_j)} (\text{PositiveIndicator})$$

$$Y_{ij} = \frac{\max(X_j) - X_{ij}}{\max(X_j) - \min(X_j)} (\text{NegativeIndicator})$$

In the formula: X_{ij} represents the original value of the j-th indicator (j = 1, 2, . . ., m) in the i-th study unit (i = 1, 2, . . ., m), and Y_{ij} represents the normalized value, ranging from [0, 1].

Table 3. Ecological resilience assessment indicator system.

Primary Assessment Indicator	Secondary Assessment Indicator	Weight	Calculation Method	Data Source
Human activities	Nighttime light index	0.1		Developing improved time-series DMSP-OLS-like data 2022 in China [47] (https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/GIYGJU) accessed on 5 October 2024
	Proximity to built-up areas	0.03	ArcGIS EucDistance	2022 10 m × 10 m European Space Agency land cover (https://esa-worldcover.org/en) accessed on 5 October 2024
	Road density	0.04	ArcGIS Road length/area	Urban road network from Open Street map

Table 3. *Cont.*

Primary Assessment Indicator	Secondary Assessment Indicator	Weight	Calculation Method	Data Source
Habitat quality	Normalized Difference Vegetation Index (NDVI)	0.05	ENVI	2022 30-m resolution annual maximum NDVI raster data in China [43] (http://www.nesdc.org.cn/sdo/detail?id=60f68d757e28174f0e7d8d49) accessed on 5 October 2024
	net primary productivity (NPP)	0.25		2023 Vegetation Net Primary Productivity (NPP) Data in China [48] (https://lpdaac.usgs.gov/products/mod17a3hgfv061/) accessed on 5 October 2024
Biodiversity	Shannon's diversity index (SHDI)	0.13	Fragstats	2022 10 m × 10 m European Space Agency land cover (https://esa-worldcover.org/en) accessed on 5 October 2024
	Connectivity index	0.4		2022 10 m × 10 m European Space Agency land cover (https://esa-worldcover.org/en) accessed on 5 October 2024

A weighted summation technique was applied, combining indicator weights with standardized values to calculate the ecological resilience of the region.

2.2.4. Landscape Resource Quality Assessment

As a system, landscapes exhibit multi-level and complex structures with diverse functions that satisfy human material and spiritual needs [49]. They hold value as resources for development, capable of producing economic, social, and environmental advantages. In China, the evaluation of landscape resources often relies on the eight tourism resource categories from the "Classification, Investigation, and Evaluation of Tourism Resources" [50], with expert scoring as the primary evaluation method. While this approach effectively encompasses natural and tangible resources, it underrepresents cultural aspects, hindering the deep exploration of diverse tourism potentials and relying on subjective evaluation [51]. Scholars have proposed that landscape resource potential can be categorized into intrinsic and service potential. Intrinsic potential indicates a landscape's fundamental capability as a tourist destination, showcasing its inherent quality. In contrast, service potential indicates the service level offered by tourism attractions based on the landscape, evaluated based on its service provision capabilities [52]. Mentougou District has abundant natural and cultural assets, such as picturesque landscapes, rich folk traditions, extraordinary cultural relics, and many temples, creating exceptional tourist conditions. It has capitalized on its diverse resources to establish rural tourism services, including farm stays and folk cultural holiday resorts. Therefore, this study selects scenic spot quality and service level as two dimensions to construct a landscape resource quality evaluation system. Scenic spot quality is assessed through three secondary indicators: scenic spot density, scenic spot grade, and intangible cultural heritage grade. The density and classification of scenic spots indicate development scale and overall quality, contributing to their reputation. At the same time, the intangible cultural heritage grade represents historical and cultural significance, supporting opportunities for innovative cultural industries. The service level dimension comprises the density of service facilities and roads. Facility density is assessed using Baidu POI data, counting points of interest in four categories: lodging, cultural and educational services, recreational facilities, and public amenities, to determine the development level of rural tourism services. The density of roads reflects transportation accessibility, a key determinant of tourist interest. To summarize, a framework of five indicators was constructed to assess the quality of regional tourism resources, refer to Table 4. Using the Analytic Hierarchy Process (AHP), weights for each indicator were derived from 10 expert surveys in relevant fields, with normalization following the approach described

in the ecological resilience evaluation section. Lastly, a weighted summation approach was utilized, combining indicator weights with standardized values to derive the tourism resource quality evaluation for the region.

Table 4. Landscape resource quality assessment indicator system.

Primary Assessment Indicator	Secondary Assessment Indicator	Weight	Calculation Method	Data Source
Scenic spot quality	Scenic spot density	0.09	ArcGIS Kernel Density	2023 Park POI data collected from the Amap (Baidu) Maps API
	Scenic spot grade	0.22		List of Open-Grade Scenic Spots in Beijing (https://whlyj.beijing.gov.cn/zwgk/tzgg/202006/t20200624_1932269.html) accessed on 5 October 2024
	Intangible cultural heritage grade	0.49		List of Intangible Cultural Heritage Projects in Mentougou District (https://www.bjmtg.gov.cn/mtg11J008/c102330/202111/f3e5f953e8964a2fb59bd09cd0e01129.shtml) accessed on 5 October 2024
Service level	Road density	0.04	ArcGIS Road length/area	Urban road network from Open Street map
	Service facility density	0.16	ArcGIS Kernel Density	2023 Park POI data collected from the Amap (Baidu) Maps API

2.2.5. Overlay Analysis

Using ArcGIS, evaluation results for debris flow susceptibility, ecological resilience, and landscape resource quality were zonally analyzed by LCAs and reclassified into high, medium, and low categories via the natural breaks method, yielding results under the safety–ecology–landscape multidimensional evaluation framework. Overlaying and comparing the three-dimensional evaluation results allowed for clustering similar LCAs through manual interpretation, followed by the classification of protection and development levels for each area. Based on the landscape characteristics and three-dimensional evaluation results, development strategies were formulated for regions of varying levels.

3. Results

3.1. Identification Results of LCAs

Following the clustering and image processing of landscape characteristic elements, 12 distinct LCTs were derived, with their spatial distribution and nomenclature illustrated in Table 5 and Figure 3.

Table 5. Landscape character types description.

Serial Number	Combination	Description
1	A2U4V2L1	Mid-altitude hilly semi-scrub grassland landscape
2	A1U2V3L1	Low-altitude terrace grassland landscape
3	A2U4V4L1	Mid-altitude hilly deciduous scrub landscape
4	A3U6V2L1	High-altitude mountainous semi-shrub steppe landscape
5	A1U1V5L5	Plain urban landscape
6	A2U4V5L3	Mid-altitude hilly deciduous broad-leaved forest landscape
7	A1U2V5L3	Low-altitude terrace deciduous broad-leaved forest landscape
8	A2U5V6L3	Mid-altitude mountainous deciduous-coniferous forest landscape
9	A2U5V2L1	Mid-altitude mountainous semi-scrub grassland landscape
10	A1U3V5L3	Low-altitude hilly deciduous broad-leaved forest landscape
11	A1U3V4L2	Low-altitude hilly deciduous scrub landscape
12	A2U5V3L1	Mid-altitude mountainous tussock grassland landscape

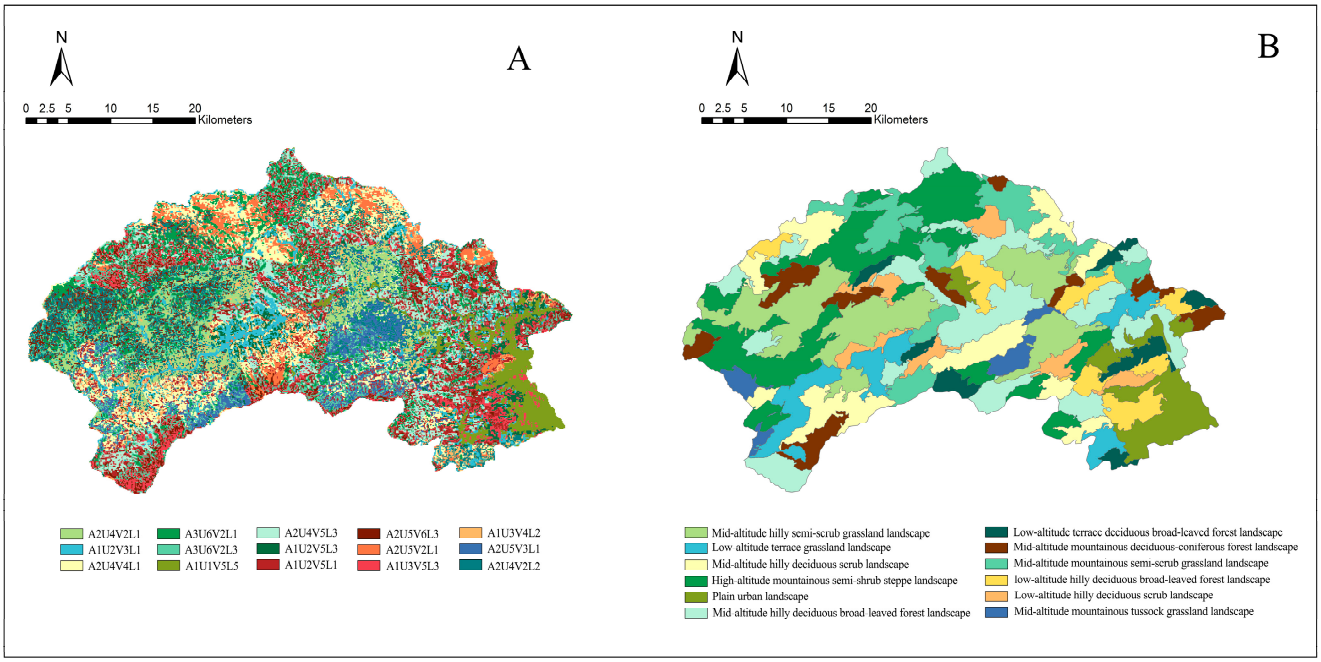


Figure 3. (**A**) Preliminary landscape character area map; (**B**) Final landscape character area map.

3.2. Debris Flow Susceptibility Assessment Results

The "Only This Variable" results in the jackknife test indicate the contribution differences of various disaster-inducing environmental factors to debris flow susceptibility. Figure 4 highlights that elevation is the primary factor impacting debris flow susceptibility, with bedrock lithology, population density, and fault zone density ranking next in importance. The results suggest that geological factors and human activities jointly influence the occurrence of debris flows. As shown in Figure 5, debris flow susceptibility exhibits an overall trend of increasing from plains to high mountainous regions. Regions with high susceptibility are concentrated in the northern high-altitude mountainous areas with significant undulations and scattered mid-altitude zones with moderate relief. Fault zone influences, weak rock stability, and significant topographic relief render these regions prone to debris flow disasters. Areas of moderate susceptibility are primarily found in the mid-altitude hills on the western side and terrace regions at the intersection of towns and mountainous zones on the eastern side. Proximity to towns has led to dense human development on slopes, disrupting rock stability and heightening the potential for debris flows. Low-susceptibility zones are concentrated in the eastern plains of urban built-up areas and central valleys with low-altitude and gentle relief. These flat terrains, free from fault zones, exhibit minimal debris flow risk and host most of Mentougou District's larger settlements.

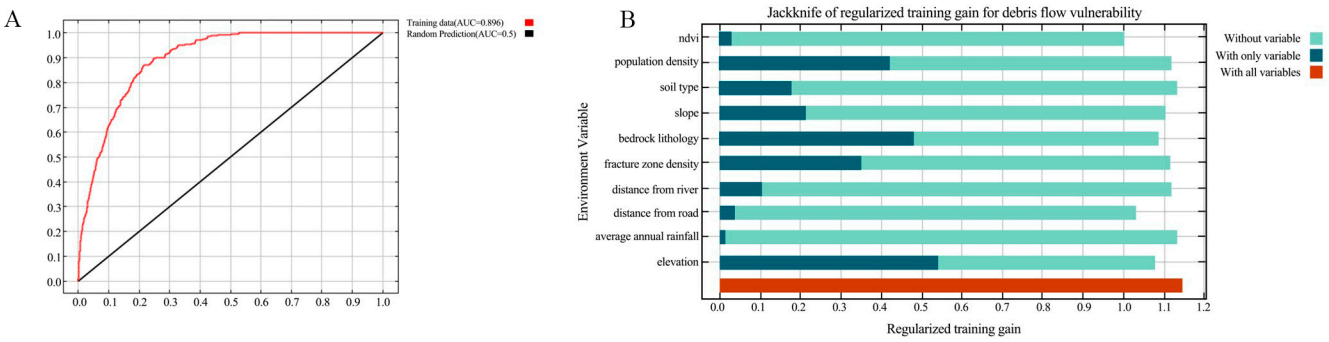


Figure 4. (**A**) AUC value for model suitability test; (**B**) The jackknife test evaluates the importance of environmental variables for debris flow susceptibility.

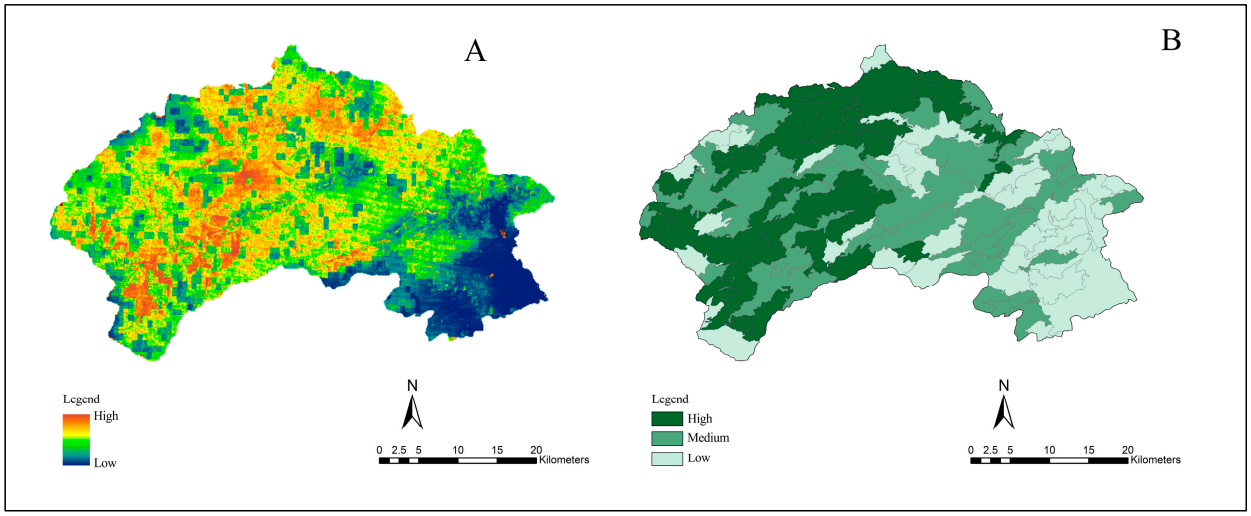


Figure 5. (**A**) Debris flow susceptibility assessment results; (**B**) Debris flow susceptibility levels.

3.3. Ecological Resilience Assessment Results

Figure 6 illustrates that the diverse regional terrain and geomorphology result in variations in vegetation and landscape patches, weakening inter-village geographical connections and causing dispersed distributions of similarly resilient ecological areas. Areas with high ecological resilience are concentrated in mid-altitude, moderately undulating hills, and mountainous regions, encompassing diverse vegetation types like coniferous-broadleaf forests, deciduous forests, shrubs, and grasslands. This habitat diversity fosters biodiversity. Limited human interference in these regions ensures robust vegetation growth. Moderate ecological resilience areas encompass diverse landscape types, including high-altitude mountainous regions with steep undulations and low-altitude hills with gentle relief. The steep terrain of high-altitude, heavily undulating mountainous areas inhibits tree layer growth, leaving semi-shrub grasslands as the dominant vegetation with poorer habitat quality. Low-altitude hills with gentle undulations near urban areas exhibit diverse vegetation communities but suffer from considerable human impact. As a result, the ecological resilience of these areas is moderately weakened. Regions with low ecological resilience encompass low-altitude plains, terraces, and small undulating hills. With a substantial proportion of hardened surfaces, vegetation in these areas consists mainly of cultivated plants, grasslands, and shrubs. Frequent human activity and fragmented green spaces contribute to low ecological resilience.

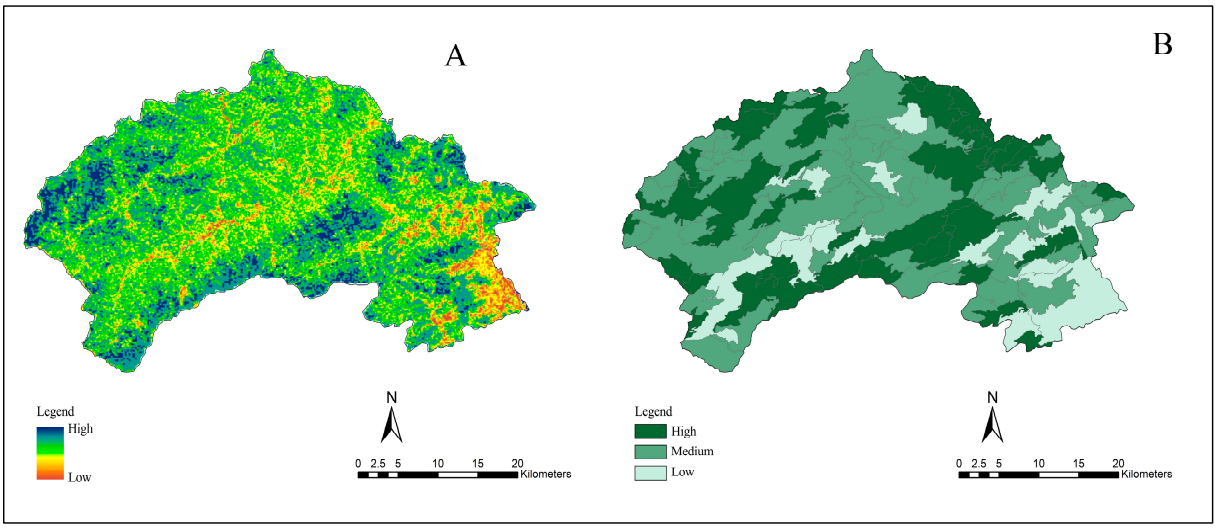


Figure 6. (**A**) Ecological resilience assessment results; (**B**) Ecological resilience levels.

3.4. Landscape Resource Quality Assessment Results

Figure 7 illustrates the landscape resource quality evaluation results. Regions with different levels of landscape resource quality are distributed in a relatively concentrated manner. Low landscape resource quality areas are predominantly found in northern high-altitude, rugged mountainous regions and mid-altitude, moderately undulating mountain zones characterized by sparse human activity and largely undeveloped landscapes. Moderate-quality landscape areas largely cover mid-altitude, moderately undulating hills. These areas feature sparse tourist facilities and attractions, with weaker accessibility owing to the absence of direct highway or national road connections. High-quality landscape resource areas coincide with Mentougou District's larger villages and urbanized areas. With a rich history of human activity, these areas host numerous historical relics and intangible cultural heritage. Supported by stunning natural backdrops, they feature well-developed natural and cultural tourist attractions with extensive infrastructure and high levels of tourism maturity. The influence of these high-quality areas has spurred the development of tourism service industries in nearby villages, with a notable tendency to expand into adjacent moderate-quality landscape regions.

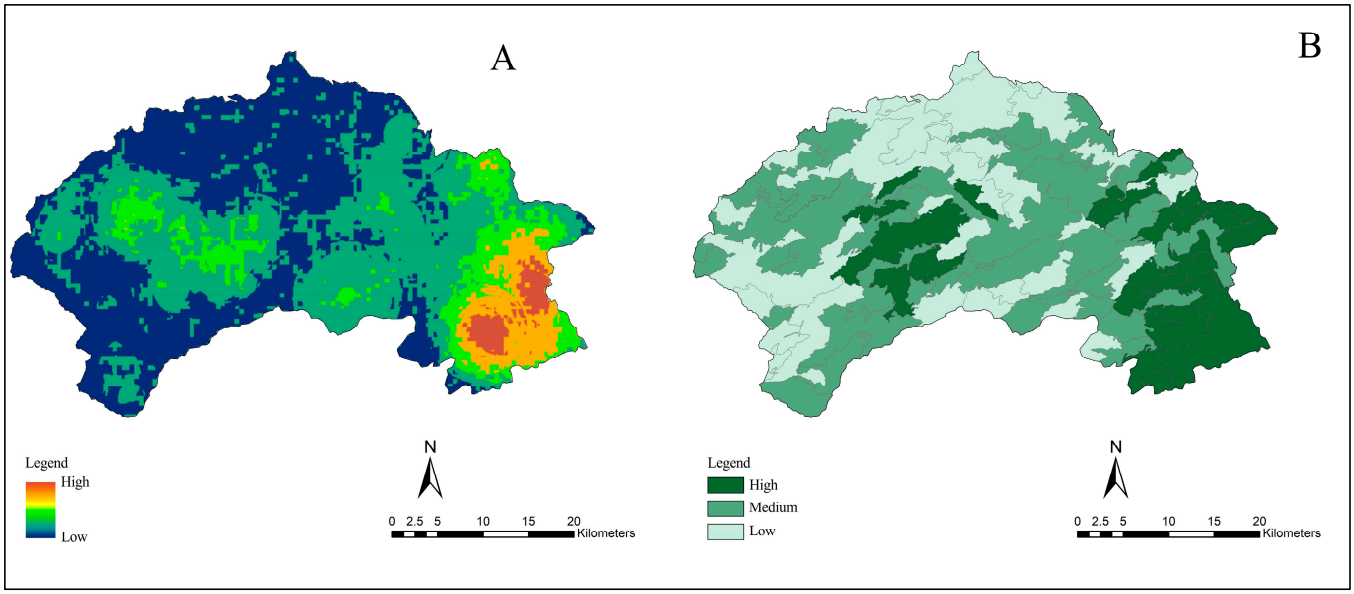


Figure 7. (**A**) Landscape resource quality assessment results; (**B**) Landscape resource quality levels.

3.5. Zone Management of LCAs

Comparing the three-dimensional assessment results for each Landscape Character Area yielded nine combination types. These were manually interpreted and grouped into four areas based on protection levels, facilitating differentiated protection and management strategies, refer to Figure 8 and Table 6. The overall evaluation outcomes were not derived by summing the three-dimensional results but through a balanced clustering process via manual interpretation. Hence, the four areas are not ranked by value but function as urban partitions, where distinct management strategies are applied based on their unique characteristics to promote sustainable utilization.

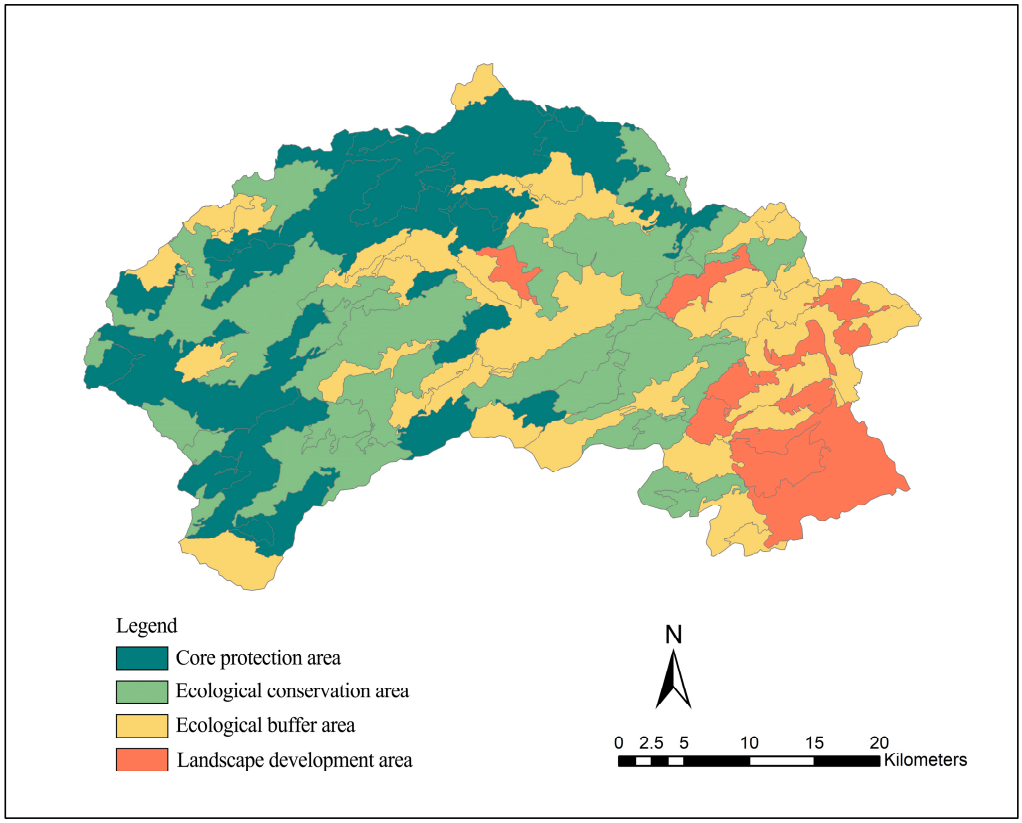


Figure 8. Zoning map for LCAs.

Table 6. Protection and development zoning with corresponding assessment results and LCAs.

	Debris Flow Susceptibility	Ecological Resilience	Landscape Resource Quality	Landscape Character Area
Core protection area	High	Medium	Low	4-1,11-1
	High	High	Low	11-2
	High	Low	Low	2-1
	High	Medium	Medium	10-1
Ecological conservation area	Medium	High	Medium	1, 3
	High	Low	High	2-2
	Low	Medium	Low	12-1
	Low	High	Low	14
	Medium	Medium	Low	4-2
Ecological buffer area	Medium	Low	High	2-3
	Medium	Medium	High	10-2
	Low	High	High	8
	Medium	Low	Medium	13
	Low	Medium	Medium	7
Landscape development area	Low	Medium	High	12-2
	Low	Low	High	6

3.5.1. Core Protection Area

Core protection areas are classified as areas with high debris flow susceptibility and low landscape resource quality. They are primarily concentrated in the deep mountainous regions of western and northern Mentougou, with some scattered in the central area. The landscape is characterized by mid- to high-altitude rugged mountains with vegetation comprising semi-shrub grasslands and deciduous coniferous forests. Due to their complex terrain, these regions are highly susceptible to debris flows and are unsuitable for human

activities or development projects. The favorable ecological conditions also support diverse habitats for various plant and animal species. Thus, ecological conservation measures must be intensified, with strict limitations on development activities. Residents in high debris flow risk zones should be ecologically relocated to safeguard lives and property. This approach ensures the preservation of the natural ecosystem's integrity and authenticity within core conservation areas, fostering effective biodiversity protection.

3.5.2. Ecological Conservation Area

Ecological conservation areas are classified as areas with moderate debris flow susceptibility, moderately high ecological resilience, and moderately low landscape resource quality. They are mainly located in the central region of the deep mountainous areas. This area features mid-altitude, moderately undulating hills with vegetation types, including semi-shrub grasslands, deciduous shrublands, and deciduous broadleaf forests. This ecosystem suffers relatively low levels of destruction from debris flows and human activities. Long-term ecological protection plans should be formulated and executed for this area to safeguard existing vegetation and biodiversity, assess ecosystem health and trends, promote ecological restoration, and implement non-invasive measures like vegetation reinforcement to mitigate debris flows. Enhanced protection and management of the Yongding River Basin water sources are necessary to avoid pollution and overuse. Rigorous control measures should be imposed on development and construction activities in this region. Leverage the region's natural landscape and ecological characteristics to host ecological education and environmental awareness initiatives, design low-impact tourism routes, restrict visitor numbers, and support eco-tourism experiences while safeguarding the environment from adverse effects.

3.5.3. Ecological Buffer Area

Ecological buffer areas are classified as areas with moderately low debris flow susceptibility, moderate ecological resilience, and moderately high landscape resource quality. Primarily situated in the valleys of deep mountainous areas and shallow hills, these regions feature mid- to low-altitude gently undulating hills and terraces, encompassing diverse vegetation and transitioning between urban environments and natural landscapes. Ecological buffer areas play a crucial role in protecting the ecosystems of ecological conservation zones and linking habitat patches. These areas can support the creation and maintenance of ecological corridors that link conservation areas with other critical ecosystems, preserving the integrity of the ecological network. Many of Mentougou District's small- and medium-sized settlements are also in these buffer areas. These areas are highly susceptible to chaotic development and excessive resource exploitation. It is crucial to enhance land use planning by defining specific purposes for various zones. Stricter enforcement against illegal construction and inappropriate land development is needed to prevent the degradation of ecological buffer areas. Implement an environmental monitoring system to periodically evaluate ecological conditions and debris flow risks, creating targeted preventive and response strategies. Promote economic transitions in villages and towns by fostering development that respects and preserves unique landscape characteristics. Leverage tourism resources to develop sustainable industries like organic agriculture and eco-tourism resorts, integrating traditional culture to align community economic growth with ecological conservation. Given the underdeveloped state of the tourism industry in this region, special care must be taken in future development to balance the conflicting interests of various stakeholders. The government should serve as a regulatory bridge, providing policy guidance and support while safeguarding the interests of residents during development. It must also steer tourism enterprises in a manner that fosters harmonious and coordinated growth among the government, residents, tourism businesses, and tourists, ultimately facilitating the sharing of benefits.

3.5.4. Landscape Development Area

The Landscape Development Areas are classified as areas with low susceptibility to debris flows, slightly below-average ecological resilience, and high-quality landscape resources. These regions represent the most developed and urbanized parts of Mentougou District, characterized by advanced tourism industries and encompassing urban areas and large settlements in shallow mountainous zones. Prolonged human–nature interactions have cultivated a diverse cultural heritage and an array of natural and cultural landmarks. Vegetation here is primarily composed of cultivated plants exhibiting limited ecological resilience. Ecological principles should be embedded in urban development to optimize limited spaces, improve green space ecosystem services, and pursue high-quality growth. The region's scenic areas are well-established, and landscape resources have been maximized. Future initiatives should center on utilizing the abundant intangible cultural heritage, uncovering new cultural dimensions, and innovating tourism models. By fostering government–business collaboration, local inheritors of intangible cultural heritage and villagers' enthusiasm and creativity can be ignited. This can drive the integration and development of intangible cultural heritage tourism resources and ultimately earn tourists' recognition. A multi-stakeholder co-creation approach can accelerate the development of the intangible cultural heritage tourism industry, minimizing further exploitation and disturbance of natural resources and ensuring the sustainable development of tourism. Infrastructure enhancements and improved public services are essential to meet the demands of residents and visitors. Targeted advancements can stimulate growth in service industries throughout adjacent areas. Despite the low risk of debris flows, emergency preparedness plans and robust disaster mitigation frameworks remain necessary. Ultimately, development in this area should harmonize with the broader landscape characteristics of the region.

4. Discussion

Identifying landscape characteristics is extensively used for combining features and defining boundaries in non-urban landscapes, facilitating the evaluation of landscape conditions within various character areas. Existing studies predominantly focus on a single dimension, such as ecological sensitivity or resilience, to evaluate LCAs, aiming to reveal how natural environments adapt and reorganize under human disturbances. Such evaluations are fundamental for defining protection levels [14] and measures for regions and have been extensively adopted worldwide [53,54]. Although ecological sensitivity evaluations provide valuable insights for ecological conservation, they need to pay more attention to the value of landscapes and the socio-economic activities of residents [55], failing to fully reveal the combined effects of multiple conflicts on regional ecology. The interplay of debris flow disasters, ecological dynamics, and development activities in Mentougou's mountainous regions shapes a complex web of human–environment conflicts. Thus, analyzing LCAs should extend beyond ecological resilience to embrace multidimensional frameworks for a holistic understanding [56,57]. This research integrates the risks associated with debris flow disasters and the development potential of landscape resources into landscape management, alongside ecological resilience, to establish a safety–ecology–landscape evaluation framework that offers comprehensive guidance for planning in hazard-prone mountainous regions.

Debris flow susceptibility measures the probability of debris flow disasters in a region, indicating the stress imposed on ecosystems and local communities. Existing research employs the Analytic Hierarchy Process (AHP) to evaluate debris flow susceptibility in the Mentougou District [25]. However, such studies are limited to gully regions, and debris flow susceptibility is assessed by overlaying disaster-inducing factors. These studies are restricted in scope and exhibit limited accuracy. Machine learning techniques excel at processing multiple disaster-inducing factors and fitting disaster datasets through autonomous learning, yielding more precise predictions. Accordingly, this research references studies employing the MaxEnt model for debris flow susceptibility evaluation in Sicily [37]. It

synthesizes disaster-inducing factors from past research [40–42] to evaluate Mentougou District's debris flow susceptibility. The model demonstrates strong predictive performance, effectively capturing debris flow susceptibility.

Furthermore, the framework integrates landscape resource quality evaluation to evaluate regional landscape resources' current development status and potential, ensuring their efficient utilization. Historically, studies have relied on subjective evaluations based on expert scoring [58]. This research utilizes an objective evaluation method, selecting scenic spot POI density, scenic spot grade, and intangible cultural heritage grades as indicators of resource quality, highlighting the significance of intangible cultural assets like culture and folklore in tourism [59]. The evaluation framework also incorporates service facilities and transportation convenience to indicate the development level of scenic areas [60]. Integrating landscape resource quality evaluations into the overall framework supports the balanced development of landscape resources, enabling them to drive regional economic growth while minimizing risks and damages arising from debris flow disasters and ecological protection constraints, thus promoting green sustainability.

The three evaluation dimensions are independent, and their results cannot be directly summed to serve as a basis for regional development decisions. Drawing on the study that developed an integrated framework of landscape character diversity, urban impact, and landscape sensitivity for zoning management in Wuhan [16], the evaluation results of the three dimensions for various LCAs were clustered. Manual interpretation was used to classify them into areas with varying protection levels for landscape management. Tailored management strategies were developed for each area to balance disaster risks, ecological resilience, and resource development, fostering a synergistic relationship among these dimensions.

Based on landscape character identification, this study establishes a three-dimensional evaluation framework integrating debris flow susceptibility, ecological resilience, and landscape resource quality to assess each Landscape Character Area. Based on these evaluations, zoning plans and management recommendations are proposed. The framework can be broadly utilized to identify landscape characteristics and delineate management areas in mountainous regions prone to natural disasters, offering guidance for planning decisions. Nonetheless, the study acknowledges three primary limitations: (1) This research limits its scope to mountainous regions, evaluating only debris flow disasters. Flooding, another significant hazard affecting the environmental safety of Mentougou District, predominantly occurs along linear features like rivers and gullies and was excluded. Future studies could integrate flood-prone areas for enhanced precision in regional management. (2) The reclassification of three-dimensional evaluation results into high, medium, and low categories for clustering purposes diminished the granularity of the original data, simplifying the information. Furthermore, the clustering process was guided by manual interpretation, adding a layer of subjectivity. Future research should investigate fully quantitative methods to retain data completeness and ensure more robust and objective management zoning. (3) This study aims to offer initial theoretical and methodological guidance for the management and conservation of disaster-prone mountainous regions. In the implementation phase of specific policies, greater attention should be paid to the involvement and coordination of stakeholders. By employing field interviews, surveys, and other investigative methods, this study will conduct a thorough analysis of the conflicts and interrelations of interests among different stakeholders. Based on these findings, appropriate strategies will be developed, ultimately creating a scientific and systematic model for symbiotic development.

While this study centers on the Mentougou District, focusing on the prevalent mudflow disasters in the area, this research framework exhibits a certain degree of universality, offering the potential for managing mountainous areas under various site conditions. The complex geology, topography, and fragile ecosystems of mountainous regions expose them to diverse disaster risks, including landslides, wildfires, avalanches, and more. Hence, future studies could incorporate the specific disaster characteristics of mountainous areas from different regions into the existing multidimensional evaluation framework, thereby

expanding its dimensions and tailoring it to regional variations. Through the ongoing refinement of the evaluation model, the stability and adaptability of the method will be improved, enabling a more effective response to disaster risks in different geographical environments and offering more scientifically grounded and practical solutions for managing disaster-prone mountainous regions.

5. Conclusions

This research describes 12 distinct LCTs in the Mentougou District using landscape character recognition and divides them into LCAs. Following this, a safety–ecology–landscape multidimensional evaluation framework is established, considering the integrated impact of debris flow susceptibility, ecological resilience, and landscape resource quality on regional development. By integrating the three-dimensional evaluation results with the defined LCAs, regions are classified into four levels of protection and development, and management strategies tailored to safety and ecological considerations in mountainous areas are proposed. Grounded in the precise identification of LCAs, the research balances the dual goals of ecological conservation and rational landscape resource utilization amidst the challenges posed by debris flow disasters. In the future, this approach can be expanded to other mountainous regions, with the model flexibly adapted to each area's specific natural conditions and disaster types. This would facilitate a scientific response to disasters and land management tailored to diverse site conditions. Additionally, further cross-regional validation will enhance the method's universality, offering comprehensive and actionable strategies for ecological governance and resource development in disaster-prone mountainous areas, thereby promoting ecological security and resource conservation in the region and achieving green, sustainable development.

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