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Study of the Sustainability of a Forest Road Network Using GIS-MCE

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Abstract: An environmentally friendly and economically efficient forest road network is the key to sustainable forest management, and it is essential to evaluate the sustainability of an established forest road network and to optimize the forest road network based on sustainability criteria. This study proposes a sustainability evaluation method for forest road networks. The evaluation index system was constructed by selecting 12 indices from the social, economic, and ecological dimensions. To improve the credibility of the weighting of the evaluation indicators, the evaluation indicators were assigned subjective and objective weights by the analytic hierarchy process and the entropy weight method, respectively, and the game theory idea was used to comprehensively assign the weights. The study area was chosen to be the Taohuajiang State-Owned Forest Farm, which is a national forest park and is also an ecological public welfare forest. The development of the forest road network in the social, economic, and environmental dimensions was calculated by adopting the evaluation method proposed in this study, and the sustainability of the forest road network in each subdivision of the study area was determined, to provide a detailed theoretical basis for the management to carry out the upgrading of the sustainability of the forest road network. The results derived from the evaluation methodology show that the sustainable development of the forest road network in the study area is "excellent". At the same time, the level of sustainability of the forest road network in different areas of the study area was also evaluated. Finally, this paper puts forward policy recommendations for optimizing the sustainable development of forest road networks. The original sustainability evaluation method in this paper provides a scientific tool for assessing the degree of sustainable development of forest road networks, which contributes to optimizing the forest road networks.

Keywords: multi-criteria evaluation; sustainable forest management; accessibility; AHP

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1. Introduction

Sustainable forest management is an approach aimed at protecting and maintaining forest ecosystems. The core principles of management include ecological balance and diversity, economic sustainability, social responsibility, and environmental protection [1–3]. A sustainable forest road network achieves the cooperation of social, economic, and environmental dimensions. Sustainable forest management can only be realized through environmentally friendly, cost-effective forest road networks and transportation systems [4,5]. It is important to conduct a comprehensive evaluation of forest road networks and clarify the parts that do not meet the sustainable development goals. The evaluation helps to upgrade the forest road network via targeted improvement and providing a scientific basis for the sustainable layout of forest road networks.

To ensure the sustainability of forests, the development of infrastructure in forest environments is essential, and forest road networks are crucial infrastructure for forest management and are necessary for environmental sustainability, timber harvesting, and forest recreation. To ensure the sustainable development of populations living in forested areas, the design of forest road networks also needs to take into account the needs of agriculture, livestock, and tourism. The assessment of the sustainability of forest roads after all needs have been met is important and will test whether forest roads take into account social, environmental, and economic development [6–9]. So far, the evaluation of forest road networks has been concerned with technical indicators such as road density, accessibility, convenience, and the degree of the environmental impact of the network [10–17]. The content of the evaluation indicators consists mainly of environment, topography [18], soil [19], hydrology [20], and social impact [21–23]. It is difficult for these evaluations to reflect the sustainability of the forest road network as a whole.

A Geographic Information System (GIS) is a spatial information system for collecting, storing, managing, computing, analyzing, displaying, and describing relevant geographic distribution data in the Earth's surface space. With the support of computer hard- and software systems, GISs are a key tool for conducting forest road planning and evaluation [24,25]. MCE is an efficient evaluation method for assessing decision-making under multiple criteria, and it is designed to provide a way to determine the most advantageous option or decision via comparison. MCE is an umbrella term for a range of methods. The main MCE methods applied to forest road network studies are the analytic hierarchy process (AHP) [26–29], fuzzy logic (FL), simple additive weighting (SAW) [30,31], the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [32,33], and the analytic network process (ANP). The MCE technique allows us to combine a set of criteria to achieve a decision according to a specific objective; the advantage of MCE is that it provides a flexible way of dealing with qualitative multidimensional environmental effects of decisions. The geographic information system (GIS)-based multi-criteria evaluation (MCE)-based model is also a method in forest road planning, which is also known as spatial MCE (S-MCE).

Assigning precise weights to the indicator system is vital for accurately evaluating the sustainability of the forest road network; the weights represent the importance of the indicators. The higher the weights, the greater the importance of the indicators. The methods of assigning weight values to indicators include subjective and objective weighting methods, but both sets of methods have certain limitations. Integrating the subjective and objective weights of each indicator to form a comprehensive weight can reflect the importance of the indicator to the maximum extent. In this study, to enhance the credibility of the index weights, game theory is applied to assign integrated weights to indices, subjective weights are assigned by the analytic hierarchy process based on the MATLAB R2018boptimization toolbox (M-AHP), and objective weights are assigned by the entropy weight method (EWM). In order to reduce the one-sidedness of subjective and objective empowerment, this study uses a combinatorial empowerment method based on game theory. Finally, a sustainability evaluation model is proposed to evaluate the sustainability of forest roads. This model helps the management department to carry out the sustainable transformation of forest roads.

This paper has the following innovations: (1) to determine the index system used to evaluate whether a forest road network meets the goal of sustainable forest development; (2) to construct a scientific and reasonable evaluation indicator system and forest road network evaluation model; (3) to carry out empirical research on selected case objects and analyze the results.

The rest of this paper is organized as follows: Section 2 introduces the overview of the study area, constructs the forest road network sustainability evaluation index system, and specifies the method of assigning weights to the indices and the evaluation model of the sustainability of the forest road network. Then, Section 3 presents a case study to calculate the sustainability of the study case. Section 4 analyzes and concludes the evaluation results of the case units in depth, summarizes the ideas and methods of this study, and finally offers suggestions for policy releases. To clearly express the research idea, a technology roadmap was prepared, as shown in Figure 1.

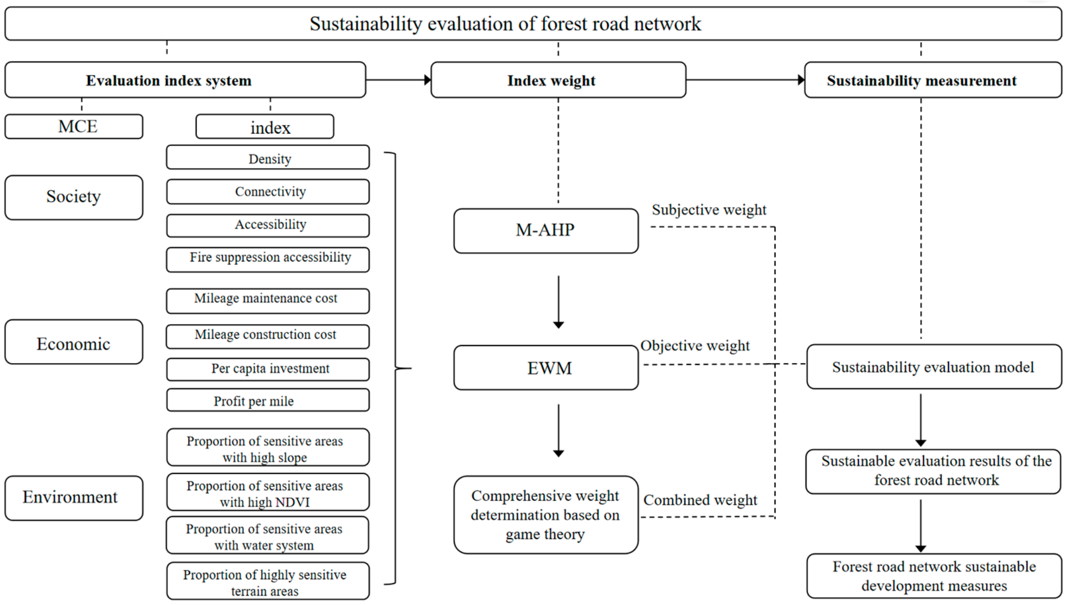

Figure 1. Research technology roadmap.

2. Materials and Methods

2.1. Study Area

Taohuajiang State-Owned Forest Farm is located in the southwest of Taojiang County, with the geographical coordinates of 112°3′1″–112°06′55″ E and 28°16′44″–28°20′26″ N. The forest vegetation in the forest farm is mainly natural forest, and the mixed evergreen and deciduous coniferous and broadleaved forest in the mid-subtropics dominates. The total operating area of the forest farm is 1492.8 hectares, and it is located in the Taohuajiang National Forest and Natural Park, with an area of 1435.87 hectares. There is 21.5 km of forest roads in the forest field, and the forest road density is 14.4 m/ha. The main functions of forest roads are forest conservation, timber collection, fire prevention, etc. However, the lack of a scientific and systematic layout of the original forest road network results in the irrational distribution of roads and high levels of environmental damage. Thus, the road network layout needs to be optimized. Figure 2 illustrates the current status of forest roads in the study area.

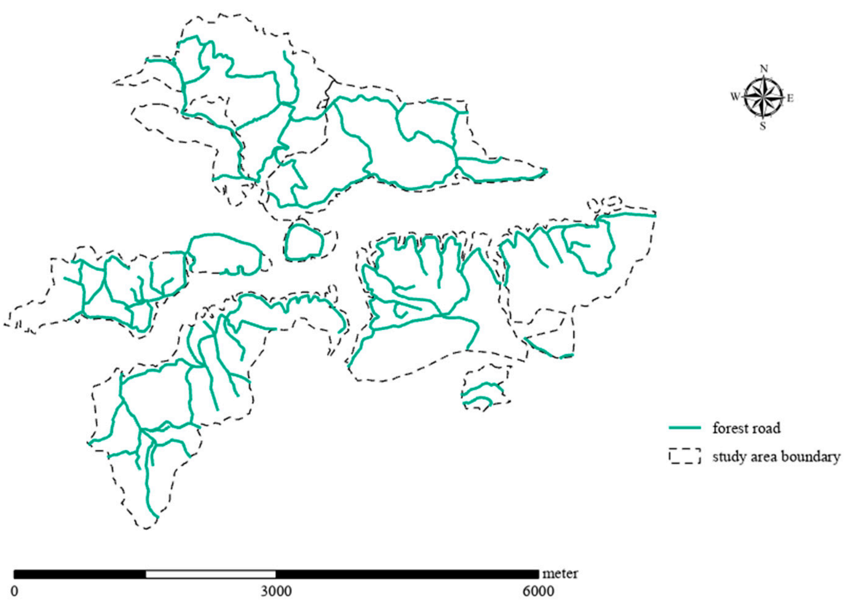

Figure 2. Overview of forest roads in the study area.

2.2. Construction of Indicator System

Following the principles of systematicity, scientificity, and objectivity, combined with previous research results and expert suggestions, the indicator system of this study was consulted by 23 experts, all of whom are engaged in forest management and come from schools, enterprises, and management departments, They all achieved academic excellence in this article, comprehensively considering the characteristics of forest road construction and the multi-objective principle of road function, and 12 indicators were selected from three aspects: social, economy, and environment. Social indicators include road density and connectivity, skidding accessibility, and fire extinguishing accessibility. In this study, the four indicators are categorized as social indicators rather than production indicators, because sustainable forest management aims to maintain the economic, social, and environmental values of forests. It is particularly important to improve the quality of life of people living in forested areas, while at the same time protecting the environment. Therefore, this study considers that road density, connectivity, and timber harvesting feasibility not only have economic and production attributes but also have social attributes. Timber harvesting feasibility, to a certain extent, represents resource availability and evacuation efficiency in emergencies; road density is also related to fire suppression and forest recreation, which is closely related to the lives of people living in the forest area; connectivity represents the degree of connectivity between roads, which is more related to fire prevention. Gathering feasibility can improve the efficiency of material transport in the forest area and help to deliver materials at special times, so these four indicators can be summarized as social indicators. Economic indicators include mileage maintenance costs, mileage new construction costs, mileage construction costs, and unit mileage income; ecological indicators include proportion of forest roads in through high-slope ecologically sensitive areas, proportion of forest roads in vegetated ecologically highly sensitive areas, proportion of forest roads in hydrologically ecologically sensitive areas, proportion of forest roads in topographic relief areas with high sensitivity. The research was constructed according to the corresponding principles. The social indicator system was constructed with primary reference to the literature [14,21,34–37]. The economic indicator system was constructed with primary reference to the literature [6,8,38–41]. The environment indicator system was constructed with primary reference to the literature [2,15,20,30,42,43], while at the same time the classification was appropriately adjusted to actual situation, including the current major modes of transport in forest areas and their average speeds, the economic restructuring of forest areas under policy regulation, and the limitations of earlier forest road network planning concepts and techniques. The official data were obtained from the official website of the forest management department, and the file name is Forest Management Programme of Taohuajiang State Forest in Taohuajiang County (2021–2030) Publication Version. Table 1 shows the evaluation system for the sustainable development of forest road networks.

Table 1. Evaluation index system for the sustainable development of forest road networks.

First-Level Indicator	Secondary Indicators	Rating	Unit	Assignment
Social indicators	Road density	>20	m/ha	5
		[15,20)		4
		[10,15)		3
		[5,10)		2
		[0,5)		1
	Connectivity	>4	/	5
		[3,4)		4
		[2,3)		3
		[1,2)		2
		[0,1)		1

Table 1. *Cont.*

First-Level Indicator	Secondary Indicators	Rating	Unit	Assignment
Social indicators	Skidding accessibility	[0,1)	h	5
		[1,1.5)		4
		[1.5,2)		3
		[2,2.5)		2
		>2.5		1
	Accessibility of fire extinguishing	>70	%	5
		[50,70)		4
		[30,50)		3
		[20,30)		2
		[0,20)		1
Economic indicators	Mileage maintenance fee	[0,4500)	CNY	5
		[4500,5500)		4
		[5500,6500)		3
		[6500,7500)		2
		>7500		1
	Mileage construction cost	[0,10)	Ten thousand CNY	5
		[10,15)		4
		[15,20)		3
		[20,25)		2
		>25		1
	Per capita investment	>200	CNY	5
		[150,200)		4
		[100,150)		3
		[50,100)		2
		[0,50)		1
	Profit per unit mileage	>9	Ten thousand CNY	5
		[6,9)		4
		[3,6)		3
		[1,3)		2
		[0,1)		1
Environmental indicators	Proportion of forest roads in through high-slope ecologically sensitive areas	[0,10)	%	5
		[10,25)		4
		[25,40)		3
		[40,55)		2
		>5		1
	Proportion of forest roads in vegetated ecologically highly sensitive areas	[0,10)	%	5
		[10,25)		4
		[25,40)		3
		[40,55)		2
		>55		1
	Proportion of forest roads in hydrologically ecologically sensitive areas	[0,15)	%	5
		[15,30)		4
		[30,45)		3
		[45,60)		2
		>60		1
	Proportion of forest roads in topographic relief areas with high sensitivity	[0,15)	%	5
		[15,30)		4
		[30,45)		3
		[45,60)		2
		>60		1

2.2.1. Indicator Calculation Method

(1) Density of forest road network

The number of forest roads per unit of forestry management area is called the forest road network density, and the measurement unit is m/ha. The calculation method is as follows:

$$DM = \frac{L}{M} \tag{1}$$

where L is the total length of the forest road, M is the total forest management area, And DM represents the road network density in the study area. Data on forest roads and forest management areas were derived from official data published by management.

(2) Connectivity

This is an indicator to consider the connectivity of the forest area road network. The connectivity of the road network refers to the ratio of the number of edges to the number of nodes that constitute the road network. A road network node is a place where a forest road intersects, or the starting and ending points of a particular forest road. The section of forest road between two nodes is called an edge. These nodes and edges form the forest road network. The degree of connectivity reflects the status of connectivity between nodes in the road network; the more road network edges connecting nodes, the higher the degree of connectivity. The calculation method is as follows [44]:

$$LTN = \frac{T_L}{\sqrt{nM}} \tag{2}$$

where LTN represents the road network connectivity in the study area, n is the number of nodes that should be connected in the forest area, M is the total area of the forest area, and TL is the total mileage of the road network. The forest road data were derived from official data released by the administration.

(3) Accessibility

After considering the accessibility indicators of the forest area road network and collecting the forest area road data, we can use a software platform like ARCGIS 10.7 to construct a dataset that automatically provides node information. To ensure the accuracy of the nodes, it is necessary to utilize the topology tool to verify the node dataset of the finalized road network, and to use network analysis tools to conduct road accessibility analysis. Accessibility represents the difficulty of reaching another node j from node i in different road networks. The accessibility of a certain point in the road network can be expressed by the average travel time Ti from this point to all points in the road network [45]; the calculation formula is as follows: TM represents the road network skidding accessibility in the study area. The forest road data were derived from official data released by the administration.

$$T_i = \frac{\sum_{j=1}^{n} T_{ij}}{n} \tag{3}$$

$$TM = \frac{\sum_{j=1}^{n} T_i}{n} \tag{4}$$

In Formulae (3) and (4), Tij represents the time from node i to node j, n represents the number of nodes in the forest road network, and for a single highway segment, the accessibility is expressed by the travel time of the segment.

(4) Accessibility of fire extinguishing

Forest fire prevention is particularly important for sustainable management. After a fire occurs, it will cause huge economic losses and even cause ecological harm. Therefore, 100 m around the road network is used as a fire extinguishing buffer zone to scientifically evaluate the accessibility when a fire occurs [46,47]. Forest road data were derived from official data released by the administration. Fire suppression buffer data were obtained by using ARCGIS 10.7 to construct buffers within 100 m of the road network.

$$\mathrm{HZ} = \frac{\mathrm{HM}}{\mathrm{M}} \quad (5)$$

where *HM* is the area of the buffer zone for fire suppression, and *M* is the total area of the forest area. The forest road network dataset in the study area was generated based on ARCGIS 10.7, according to the official data provided by the management department. *HZ* represents the road network accessibility of fire extinguishing in the study area.

(5) Mileage maintenance fee

Considering the index of maintenance cost per kilometer of road facilities in forest areas per year, the calculation formula is as follows. Annual data on the total cost of road maintenance and total road mileage were derived from official data published by the forest administration:

$$YH = \frac{Y}{L} \quad (6)$$

where *YH* represents the maintenance cost per kilometer of the forest road network in the study area, *Y* represents the total road maintenance cost per year, and *L* represents the total mileage of the road.

(6) Mileage construction cost

Considering the construction cost per kilometer of road facilities in forest areas per year, the calculation formula is as follows. The source of data on the total annual forest road construction costs in forested areas and the total mileage of roads of forested areas was the official data published by the forest administration:

$$R = \frac{J}{L} \quad (7)$$

where *R* represents the construction cost per kilometer of the forest road network in the study area, *J* represents the total annual forest road construction costs, and *L* represents the total mileage of roads.

(7) Per capita investment

Considering the index of per capita investment in forest area road facilities, the calculation formula is as follows. The source of data on the total annual cost of road construction in forested areas and the total population of forested areas was the official data published by the forest administration:

$$TA = \frac{J}{RK} \quad (8)$$

where *TA* represents the per capita investment per kilometer of the forest road network in the study area, *J* represents the total annual forest area road construction costs, and *RK* represents the total population of the forest area.

(8) Profit per unit mileage

After timber felling and under-forest economic crops are harvested, the forest road network is the most important external transportation channel. Therefore, the forest road network is highly related to the economic development of the forest area. Profit per unit mileage can intuitively show the contribution of the forest road network to the economy. Data on the total annual income of forest areas and the total mileage of forest roads were derived from official data released by forest management authorities, and the total annual income of forest areas generally includes income from sales of forest products, forest tourism, etc.

$$SY = \frac{ZS}{L} \quad (9)$$

where SY represents the profit per kilometer of the forest network in the study area, ZS represents the total annual income of the forest area, and L represents the total mileage of the road network.

(9) Proportion of forest roads in through high-slope ecologically sensitive areas [12,13]

The digital elevation model (DEM) was taken from the Geospatial Data Cloud, based on the DEM data of the passage area. The surface analysis tool in ARCGIS 10.7 software was used for slope analysis. After obtaining the slope value of the mountain, we continued to use the reclassification tool in the software to divide the slope into five categories. The higher the slope, the more ecologically sensitive. The higher the degree, the greater the risk of forest road operation. SP represents the length of forest roads that pass through ecologically sensitive areas on high slopes as a proportion of the total forest road length. Table 2 demonstrates the slope classification method.

Table 2. Slope sensitivity classification standards of the study area.

Index Represent	Interval	Grading
SP	$0 \leq SP < 10$	Non-sensitive
	$10 \leq SP < 20$	Low sensitivity
	$20 \leq SP < 30$	Moderately sensitive
	$30 \leq SP < 40$	Highly sensitive
	$SP > 40$	Extremely sensitive

(10) Proportion of forest roads in vegetated ecologically highly sensitive areas

The normalized difference vegetation index (NDVI) is constructed based on the absorption of vegetation foliage in the red band and reflection in the near-infrared band in the study area, which can effectively reflect the vegetation growth status, plant biomass, leaf area index, and other vegetation indicators. The higher the NDVI, the better the ecological environment—that is, the stronger the sensitivity. Therefore, during construction of the forest highway, it is necessary to avoid high-sensitivity areas as much as possible. In this study, the NDVI is classified into five categories, which are defined as extremely sensitive, highly sensitive, moderately sensitive, low-sensitivity, and non-sensitive areas. In this study, the NDVI images of the study area come from the Landsat 8 satellite data of the Geospatial Data Cloud website.

After calculating the NDVI value in the study area, we reclassified the NDVI based on the classification interval data, converted the data into vector data, used the intersection tool to superimpose the road network in the study area and the NDVI reclassification area, and finally calculated the ratio of road length to total length in highly sensitive areas. The reclassification tool in ARCGIS 10.7 was used to classify the NDVI into five levels. The reclassification numbers were assigned as shown in Table 3, where NT represents the length of forest roads that pass through ecologically sensitive areas of vegetation, as a proportion of the total length of forest roads.

Table 3. Vegetation sensitivity classification standards in the study area.

Index Represent	Interval	Grading
NT	$0.016 \leq NT \leq 0.1$	Non-sensitive
	$0.1 \leq NT \leq 0.15$	Low sensitivity
	$0.15 \leq NT \leq 0.2$	Moderately sensitive
	$0.2 \leq NT \leq 0.25$	Highly sensitive
	$NT > 0.25$	Extremely sensitive

(11) Proportion of forest roads in hydrologically ecologically sensitive areas

Indicators such as the flow direction, flow rate, confluent river network, and natural watersheds in the study area comprehensively reflect the hydrological conditions in the study area. In this study, the 100 m near the river course was confirmed as an ecological buffer zone. The closer the forest road is to the river area, the stronger the sensitivity and the higher the risk factor. The digital elevation model (DEM) was taken from the Geospatial Data Cloud. This study was based on the DEM data of the study area and used the surface analysis tool of ARCGIS 10.7 to conduct hydrological analysis. After drawing the ecological buffer zone, we used the intersection tool of ARCGIS 10.7 to superimpose the forest road and the ecological buffer zone, and then we calculated the proportion of the forest road length in the buffer area to the total forest road length, where WA represents the length of forest roads that pass through ecologically sensitive areas of waterways, as a proportion of the total length of the forest roads (Table 4).

Table 4. Hydrological ecological sensitivity classification standards in the study area.

Index Represent	Interval	Grading
WA	$0 \leq WA \leq 15$	Non-sensitive
	$15 \leq WA \leq 30$	Low sensitivity
	$30 \leq WA \leq 45$	Moderately sensitive
	$45 \leq WA \leq 60$	Highly sensitive
	$WA > 60$	Extremely sensitive

(12) Proportion of forest roads in topographic relief areas with high sensitivity

The digital elevation model (DEM) was taken from the Geospatial Data Cloud. Based on the elevation terrain data calculated, we set the neighborhood distance to 3 pixels, calculated the maximum elevation value and minimum elevation value in the area, and finally used the raster calculator tool to determine the terrain difference in the area and construct the research. The terrain relief of the area was measured, and the length of forest roads located in areas with high sensitivity to terrain relief was calculated as a proportion of the total forest roads, where QF represents the length of forest roads that pass through ecologically highly sensitive areas of undulation, as a proportion of the total forest road length (Table 5).

Table 5. Topographic relief sensitivity classification standards of the study area.

Index Represent	Interval	Grading
QF	$QF > 40$	Extremely sensitive
	$40 \leq QF \leq 30$	Highly sensitive
	$30 \leq QF \leq 20$	Moderately sensitive
	$20 \leq QF \leq 10$	Low sensitivity
	$QF < 10$	Non-sensitive

2.2.2. Index Empowerment

We used the combined weighting method to calculate the index weights. With fully utilizing the basic attributes and advantages of subjective and objective weighting methods, the influence of the shortcomings of subjective and objective weighting on the evaluation results was weakened over time.

1. Calculation of subjective weights by the analytic hierarchy process based on the MATLAB R2018boptimization toolbox (M-AHP)

The analytic hierarchy process (AHP) is a math-based GIS-compatible and multidisciplinary decision method that is utilized in various fields and also in the planning of routes, construction, and maintenance of roads. At the same time, the AHP is also preferred and used in forestry studies [48].

In this study, the subjective weights were established using the analytic hierarchy process based on the MATLAB R2018boptimization toolbox (M-AHP), a progressive five-scale method was used to construct a judgment matrix based on the analytic hierarchy process, and the judgment matrix was used to calculate the weight of the evaluation index. In order to improve the accuracy of the calculation, after obtaining the judgment matrix, MATLAB R2018b software was used to solve the problem; the specific construction steps were as follows:

(1) Build the construction sequence, including the target layer, criterion layer, and index layer, to establish an evaluation index system.

(2) Invite an expert group to compare the indicators at each level, and determine the importance of each element at the same level to directly compare the matrix A.

$$A = \left[a_{ij}\right]_{n \times n}$$

where a_{ij} is the level of importance of index i relative to index j. Among them, $a_{ij} > 0$, when $i = j$, $a_{ij} = 1$, and the sum of a_{ij} and a_{ji} is their reciprocal value.

(3) Consistency check: Calculate the consistency test index CR. When $CR < 0.1$, the consistency of the judgment matrix meets the requirements. The calculation formula is as follows:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{10}$$

$$CR = \frac{CI}{CR} \tag{11}$$

where CI is the consistency index, $\lambda_{\max}$ is the maximum eigenvalue of the judgment matrix, and n is the order of the matrix.

CR is the consistency index, while RI is the average random consistency index.

(4) Calculate index weight (Table 6)

$$Qi = \frac{\left(\Pi_{j=1}^{n} aij\right)^{\frac{1}{n}}}{\sum_{i=1}^{n}\left(\Pi_{j=1}^{n} aij\right)^{\frac{1}{n}}} (i = 1, 2, \ldots) \tag{12}$$

Table 6. Meaning of the five-scale method.

Scale Value	Implication
1	Indicator i is as important as indicator j
3	Indicator i is more important than indicator j
5	Indicator i is more important than indicator j
2, 4	Between the two adjacent judgments above
Reciprocal value	The comparison result between indicator i and indicator j is reciprocal to that between indicator j and indicator i

2. Calculation of objective weight by the entropy weight method (EWM)

The analytic hierarchy process (AHP) is capable of determining the relative significance of indicators. However, this approach is subject to a considerable level of subjectivity. Specialists may hesitate to employ the AHP evaluation. Hence, it is imperative to implement an objective weight analysis approach for assessing the significance of all indicators. In this case, the entropy weight method was selected to allocate objective weights. The entropy weight method has the advantages of not being affected by the subjective wishes of the evaluators, and it clearly and effectively reflects the relationship between index data changes and index weights. This approach is capable of assessing the significance of indicators at the cost of the fewest data sources, thereby reducing subjectivity and minimizing information loss. A total of twenty-three experts were invited to participate in an online questionnaire aimed at assessing the level of significance associated with each indication; the specific construction steps were as follows:

Step 1: Build a decision matrix:

$$X = \begin{pmatrix} x_{11} & \cdots & x_{1m} \\ \vdots & \vdots & \vdots \\ x_{n1} & \cdots & x_{nm} \end{pmatrix} \tag{13}$$

Step 2: Normalize the decision matrix X:

$$g_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} X_{ij}} (i = 1, 2, \ldots, n; j = 1, 2, \ldots, m) \tag{14}$$

Step 3: Find the information entropy of the index:

$$E_j = -\frac{1}{\ln n} \sum_{i=1}^{n} g_{ij} \ln g_{ij} \tag{15}$$

Step 4: Calculate the utility index of each index:

$$Y_j = 1 - E_j \ (\mathrm{j} = 1, 2, \ldots, \mathrm{m}) \tag{16}$$

Step 5: Calculate index weight Qj:

$$Q_j = \frac{Y_j}{\sum_{j-1}^{n} Y_j} (\mathrm{j} = 1, 2, \ldots, \mathrm{m}) \tag{17}$$

3. Comprehensive weight determination based on game theory

How to integrate the subjective and objective weights of each index to form a comprehensive weight to truly reflect the importance of the index in the system is the key to this study. There have been several studies that have made progress, such as the RANCOM method, the game theory method, etc. [49]. This study adopts the game-based method of determining the comprehensive weight of the theory [50], compensating for the shortcomings of their respective systems in order to avoid the subjectivity of the hierarchical approach and overcome the objectivity of the entropy approach. The subjective weight Q1 determined by the five-scale analytic hierarchy process and the objective weight Q2 determined by the entropy weight method are used for mutual games, and the optimal comprehensive weight Q* that makes the game between the two sides reach a balance is sought. The specific process is as follows:

Step 1: Linear combination of weights:

$$Q = \alpha_1 Q_1 + \alpha_2 Q_2 \tag{18}$$

Step 2: Based on game theory, the optimal combination weight is determined and the optimal combination coefficient $\alpha*$ is obtained, minimizing the sum of deviations between $Q*$ and Q1 and Q2:

$$\begin{aligned} &\min(\|Q^* - Q_1\|_2 + \|Q^* - Q_2\|_2) \\ &\quad = \min(\|\alpha_1^* Q_1 + \alpha_2^* Q_2 - Q_1\|_2 + \|\alpha_1^* Q_1 + \alpha_2^* Q_2 - Q_2\|_2) \\ &\quad \alpha_1^*, \alpha_2^* > 0, \alpha_1^* + \alpha_2^* = 1 \end{aligned} \tag{19}$$

Step 3: According to the differential properties, perform the optimal first-order derivation of Formulae (18) and (19), as shown in Formula (20):

$$\begin{cases} \alpha_1 Q_1 (Q_1)^T + \alpha_2 Q_1 (Q_2)^T = Q_1 (Q_1)^T \\ \alpha_1 Q_2 (Q_1)^T + \alpha_2 Q_2 (Q_2)^T = Q_2 (Q_2)^T \end{cases} \tag{20}$$

Step 4: Confirm the optimal comprehensive weight matrix $Q = Q_1^*, Q_2^*, \ldots, Q_m^*$:

$$Q^* = \alpha_1^* Q_1 + \alpha_1^* Q_2 \quad (21)$$

2.2.3. Sustainability Evaluation Criteria

Build a sustainability evaluation model, as shown in the figure below.

$$K = \sum_{j=1}^{mi} \frac{w_{ij} x_{ij}}{50} \quad (22)$$

where x_{ij} represents the standardized value of the j-th index data of the i-th subsystem, ω_{ij} represents the weight of the *j-th* index of the *i-th* system, and *mi* represents the number of secondary indicators contained in the *t-th* first indicators. This study adopts a four-level evaluation method: excellent, good, poor, and particularly bad. The specific evaluation methods are shown in Table 7.

Table 7. Evaluation method of the sustainable development level of forest road networks.

Index	Section	Evaluation Level
Sustainable development level of forest road network	(0.7,1]	Excellent
	(0.5,0.7]	Good
	(0.3,0.5]	Poor
	(0,0.3]	Particularly bad

3. Results

3.1. Indicator Values

3.1.1. Calculation of Social and Economic Indicators

The calculation results of social indicators and economic indicators in the study area are shown in Table 8.

Table 8. Calculation results of social and economic indicators in the study area.

First level Indicator	Index Represent	Calculated Value
Social indicators	DM	14.4 m/ha
	LTN	2.54
	TM	0.75 h
	HZ	29.96%
Economic indicators	YH	5787.26 CNY
	R	16.1 ten thousand CNY
	TA	29.59 CNY
	SY	9.43 ten thousand CNY

3.1.2. Calculation of Environmental Indicators

Using the calculation methodology already constructed above, the environmental indicators were calculated as shown in Table 9 and Figure 3.

3.1.3. Sustainability Evaluation Results

In order to further improve the accuracy and objectivity of the index weights, this study introduces the idea of game theory. We carried out the final combination weighting, compiled the algorithm and ran it in MATLAB R2018b software, and finally obtained the combination weights, as shown in Table 10. Adding the weights of the four social indicators gives a total weight of 0.3091 for the social indicators, adding the weights of the four economic indicators gives a total weight of 0.3268 for the economic indicators, and adding the weights of the four environmental indicators gives a total weight of 0.3641 for the environmental indicators, giving a total weight value of 1 for all indicators.

Table 9. Calculation results of environmental indicators in the study area.

Index	Standard of Highly and Extremely Sensitive Areas	Calculation Result (%)
Proportion of forest roads in through high-slope ecologically sensitive areas	Slope greater than or equal to 30 degrees	3.07
Proportion of forest roads in vegetated ecologically highly sensitive areas	NDVI greater than or equal to 0.2	23.01
Proportion of forest roads in hydrologically ecologically sensitive areas	The distance between the road and the river is less than or equal to 100 m	35.7
Proportion of forest roads in topographic relief areas with high sensitivity	The relief of the terrain is greater than or equal to 30 degrees	0.5

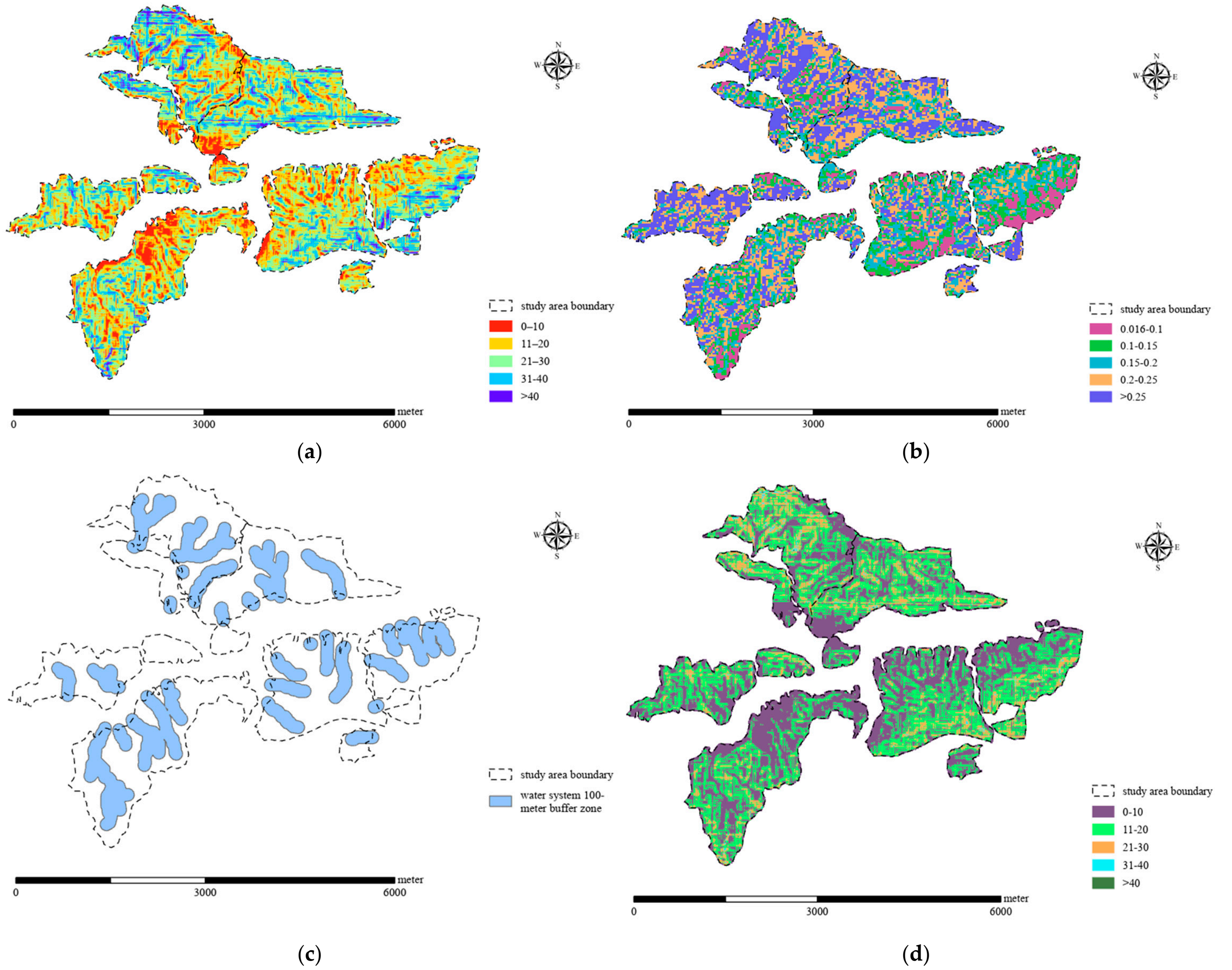

Figure 3. Calculation results of environmental indicators in the study area: (**a**) Slope classification map of the study area. (**b**) Vegetation classification map of the study area. (**c**) Schematic diagram of the hydrologically ecological buffer zone in the study area. (**d**) Topographic relief sensitivity classification map of the study area.

Table 10. Combination weights of sustainable evaluation indicators for the forest road network in the study area.

Serial Number	Index	Combination Weight	
1	Road density	0.0771	0.3091
2	Connectivity	0.0847	
3	Skidding accessibility	0.0731	
4	Accessibility of fire extinguishing	0.0742	
5	Mileage maintenance fee	0.1114	0.3268
6	Mileage construction fee	0.0911	
7	Per capita investment	0.0804	
8	Profit per unit mileage	0.0439	
9	Proportion of forest roads in through high-slope ecologically sensitive areas	0.0929	0.3641
10	Proportion of forest roads in vegetated ecologically highly sensitive areas	0.0641	
11	Proportion of forest roads in hydrologically ecologically sensitive areas	0.1225	
12	Proportion of forest roads in topographic relief areas with high sensitivity	0.0846	
	Total weight value	1	

3.2. *Sustainability Evaluation*

According to the evaluation formula and using MATLAB R2018b software for calculation, the sustainable evaluation results of the forest road network in the study area can be obtained as shown in Table 11. The evaluation level is excellent. This is due to the great emphasis on forest infrastructure construction in the study area and the competent authorities and policy tilt. Based on the above study, the total weight of social indicators is 0.3091, the total weight of economic indicators is 0.3268, and the total weight of environmental indicators is 0.3641. In order to reflect the sustainability scores of each dimension, firstly, the degree of sustainability of each dimension was calculated in accordance with the evaluation model, and a visual presentation was carried out so that the sustainability evaluation score of each dimension could be obtained.

Table 11. Sustainable evaluation results of the forest road network in the study area.

Serial Number	Index	Calculation Results	Score	
1	Road density	14.4 m/ha	3	0.2
2	Connectivity	2.54	3	
3	Skidding accessibility	0.75 h	5	
4	Accessibility of fire extinguishing	29.96%	2	
5	Mileage maintenance fee	5787.26 CNY	3	0.2
6	Mileage construction fee	16.1 ten thousand CNY	3	
7	Per capita investment	29.59 CNY	1	
8	Profit per unit mileage	9.43 ten thousand CNY	5	
9	Proportion of forest roads in through high-slope ecologically sensitive areas	3.07%	5	0.3
10	Proportion of forest roads in vegetated ecologically highly sensitive areas	23.01%	4	
11	Proportion of forest roads in hydrologically ecologically sensitive areas	35.7%	3	
12	Proportion of forest roads in topographic relief areas with high sensitivity	0.5%	5	
	Sustainability rating score		0.7	
	Rating		Excellent	

Figure 4 shows the sustainability of forest roads in different parts of the study area, analyzed in depth from the northern, southwestern, and southeastern parts of the study area.

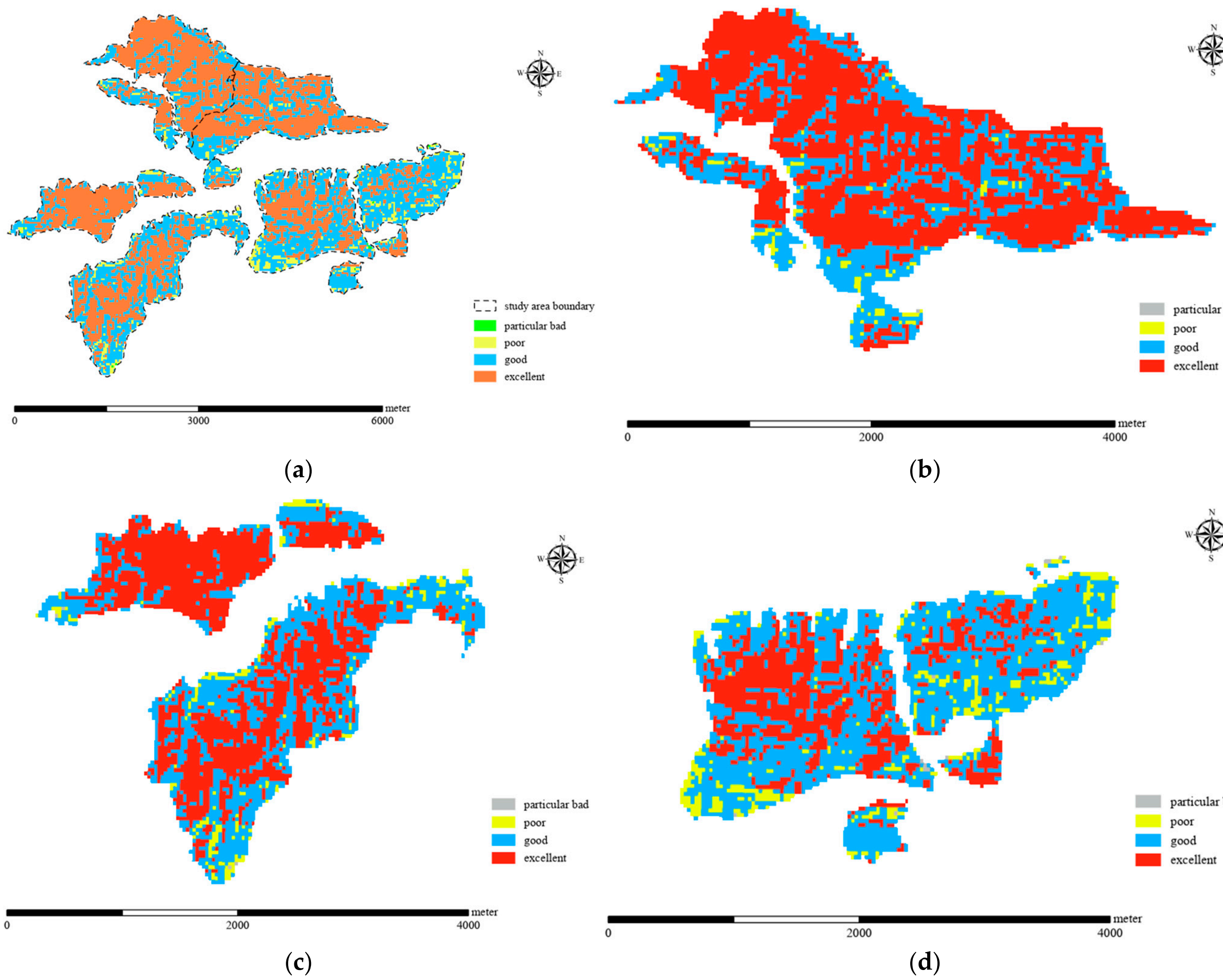

Figure 4. Results of the sustainability assessment of forest roads in the study area: (**a**) Overall sustainable development of the forest road network in the study area. (**b**) Sustainable development of forest road networks in the northern part of the study region. (**c**) Sustainable development of forest road networks in the southwest of the study region. (**d**) Sustainable development of forest road networks in the southeastern part of the study region.

3.2.1. Northern Part of the Study Area

The northern part of the study area has higher slopes, more undulating terrain, and numerous waterways. Therefore, when the forest road network was laid out in the early stages, areas with flatter terrain and farther away from the river network were generally selected for the construction of the forest road network, and the road density was also arranged more reasonably. In general, most of the forested areas are unaffected by road construction, and there is little human disturbance because of the high slopes, except for the forest management activities of the administration. However, there are also a few "poor" areas, which are close to settlements and around waterways, where the degree of sustainability is affected by higher levels of human disturbance; there are still 2.09 percent of regions with "poor" and 0.04 percent with "particularly poor" forest road network sustainability.

3.2.2. Southwest of the Study Area

In the southwest of the study area, the terrain is relatively flat and the NDVI is high, but due to the concentration of the river network it is impossible to completely avoid the road network layout. Hence, despite the high density of the road network, there are still

4.16 percent of regions with "poor" and 0.08 percent with "particularly poor" forest road network sustainability.

3.2.3. Southeastern Part of the Study Area

In the southeastern part of the study area, there are more areas with "poor" or "particularly bad" sustainability because the forest road network is built along the river system. At the same time, factors such as the high degree of terrain relief and the low NDVI also contribute to the low level of sustainable development; there are still 8.43 percent of regions with "poor" and 0.26 percent with "particularly poor" forest road network sustainability. In some areas, there are not even any forest roads yet, where it is not possible to carry out forest management properly and the areas are not accessible; therefore, the forest road network in the southeastern of the study area has the lowest level of sustainable development.

Table 12 shows the sustainability of forest roads in different parts of the study area, and it can be seen that 64.83 percent of the northern part of the study area is in excellent condition, 53.68 percent of the southwestern part of the study area is in excellent condition, and 29.66 percent of the southeastern part of the study area is in excellent condition. Each section has a poor section and a particularly bad section.

Table 12. Sustainability evaluation results of the forest road network in the study area.

	Northern Part of the Study Area	Southwestern Part of The Study Area	Southeastern Part of the Study Area
Excellent	64.83%	53.68%	29.66%
Good	33.04%	42.08%	61.65%
Poor	2.09%	4.16%	8.43%
Particularly bad	0.04%	0.08%	0.26%

4. Discussion and Conclusions

4.1. Discussion

(1) The calculation results indicate that the social and environmental indicators perform well, whereas the economic indicators underperform. The forest roads in the study area cause a certain degree of environmental damage when they pass through the ecologically highly sensitive areas of the river network, but the proportion of damaged areas in the overall area is small. The poor performance of the economic indicators is because the study area, in recent years, has begun to change its economic development model, shifting from the traditional economic output to multi-industrial development. The tourism industry has become part of the multi-industry development. Another reason is that the cost of transporting timber (mainly bamboo) to the collection points is high, and the acquisition and distribution of the forest economy products depend mainly on human labor. The better performance of social indicators is due to the published policy that helps to build forest roads in the study area and to provide travel convenience for forest dwellers. The regional sustainability calculated by applying the model cannot show the sustainability of the subdivided regional road network.

(2) For the northern part of the study area, due to the high proportion of ecologically sensitive areas, it is no longer suitable to build too many new roads, and the accessibility and connectivity of forest roads should be improved by adding more roads, while the grade of the existing roads should be improved to avoid reducing the efficiency of transport in bad weather, such as rainy days, when vehicles cannot enter the forest area. For the southwestern part of the study area, the road network near the river should be ecologically restored by replanting vegetation and reinforcing soil erosion areas. For the southeastern part of the study area—the forest roads with "poor" and "particularly bad" degrees of sustainability—ecological restoration should be accelerated; at the same time, consideration should be given to building new roads in order to guarantee ecological sustainability. For the areas where forest roads have not yet been planned, comprehensive consideration

should be given to social, economic, and environmental factors at the planning stage, based on the sustainable management of forests.

(3) For the selection of the 12 indicators, it was mainly based on the expert consultation method and the literature research method. The sustainable evaluation of forest roads is an exploratory study, which means that there is not much of a research base yet, so the selection of indicators and the classification of the calculated values of different indicators are dependent on the expert consultation method and existing literature, and the evaluation indicator system will be further improved in future research. Meanwhile, in the calculation of road construction indicators, only the past construction costs were considered; a conversion of past costs to today's costs was not considered but will be considered in future research. At the same time, defining the sustainability of a forest road network requires not only a set of indicators assessed by forest technicians or academics, but also a public assessment of the same road network (public stakeholders). The continuous work of future research on indicators assessed by users will enhance the completeness of the sustainability assessment of forest road networks. The calculation method of the indicators will also be further improved in future research.

(4) The sustainable evaluation concept and evaluation method for the forest road network proposed in this study are innovative in the field of forest road research. Firstly, existing studies have focused on planning forest roads and proposing specific construction methods, but these studies lack an evaluation of forest road network planning. The forest road sustainability evaluation proposed in this paper builds a connection between the concept of forest road network sustainability and practical operation [51,52]. Secondly, the forest sustainability evaluation model in this study is targeted and operable; 12 secondary indicators were constructed from the social, economic, and environmental dimensions, and the calculation method of the indicators was clarified. The weighting analysis of the indicators avoids the defects of subjective and objective weighting methods and innovatively adopts game theory thinking for the combination of weighting.

4.2. Conclusions

This paper is committed to the evaluation of the sustainable development of forest road networks based on the GIS-MCE method, taking Taohuajiang National Forest as the research target and further constructing the evaluation index system of sustainable development of the forest road network from three dimensions: society, economy and environment. A sustainability evaluation model was constructed to calculate the sustainability of the forest road network in the study area and to analyze the sustainability of specific subregions. The conclusions drawn from this research are as follows:

(1) The sustainability of forest roads is to be quantified with specific values. Carrying out a one-dimensional evaluation of forest road networks makes it difficult to reflect the level of sustainable development of forest road networks and provide reasonable suggestions for road network optimization. The prerequisite for the sustainable development evaluation of forest road networks is a scientific indicator system, guided by the theory of sustainable forest development and constructed to provide a basis for the assessment of the sustainable development of forest roads.

(2) The method of assigning weights to the indicators is critical to the results of the study. This study first assigned subjective and objective weights using the analytic hierarchy process based on the MATLAB R2018boptimization toolbox (M-AHP) and entropy weight method, and then it used the idea of game theory to obtain the final comprehensive assignment. This approach enhances the credibility of the weights of the evaluation indicator system; it also supports targeted optimization of the forest road network.

(3) A sustainability assessment of existing forest roads is a prerequisite for road network optimization. For forest areas where there is a lack of science in the planning of forest roads, the lack of systematic planning and low-density roads in the early construction jointly limit the efficiency of transportation capacity and forest fire fighting. Therefore, the upgrading of forest roads needs to calculate specific indicators and analyze the weak

points based on the existing forest road network. The evaluation index system and methods proposed in this study provide theoretical support for forest road optimization, and the evaluation results can clarify the unreasonable part of the construction, contributing to strategic improvement.

4.3. Policy Recommendations

Based on the above research findings, this paper puts forward the following policy recommendations:

(1) Constructing a multidimensional planning system for forest roads: With sustainable forest management as the core concept, the management department carries out sustainable planning and layout of forest roads at three levels: strategic, tactical, and operational. The planning of the strategy is mainly to determine the general principles and methods of the road layout. Tactical planning involves minimizing the negative impacts of roads on ecosystems and designing forest roads to reduce the negative impacts on the locals and socio-ecology. The operational planning involves giving specifications for standardized construction.

(2) Carrying out targeted sustainability upgrades on forest roads: The management department optimizes the construction of forest roads based on the results of the sustainability assessment. However, the optimization work does not aim at increasing road density but, rather, at improving the accessibility and connectivity of forest roads through appropriate additions. For forest roads with significant ecological damage, rerouting or introducing vegetation and trees are good choices to restore ecosystem function. Economic development should also be considered in the planning of forest road networks. The economic restructuring promotes sustainable forestry and the development of non-timber forest products; furthermore, it provides sustainable employment opportunities for local communities. The planning of the road network should be consistent with the principles of sustainable forestry management, where the sufficient capacity of transportation and improved forest carbon sinks are equally important.

(3) Improvement of the sustainability evaluation system for the whole process of the forest road network: The sustainability of forest roads is reflected not only in the planning stage but also in the construction and operation stages. Therefore, the management should establish an evaluation index system for the levels of sustainable development, development capacity, and development coordination of forest roads, set up a monitoring system to track the actual impact of upgrading projects, and make timely adjustments.

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