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Research on the Prediction of Forest Fires in the Central Yunnan Region Based on the Coupling Coordination Degree

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Abstract

This study aims to reveal the formation mechanism of forest fires in the central Yunnan region through a multi-dimensional coupling coordination degree model, providing a scientific basis for fire risk early warning and the construction of ecological security barriers. Based on multi-source data including climate, vegetation, terrain, and human factors, methods such as factor analysis, coupling coordination degree model, and GIS spatial analysis were adopted to quantify the interaction between the natural and social systems, and to construct a regionally adaptable fire risk early warning model. [Results] The results show that the system coupling degree (C value) remains continuously higher than 0.7, reflecting a significant synergistic effect of multiple factors. The coordination degree index (D value) is generally in the primary coordination stage but shows an upward trend. In Yuxi City, the proportion of high fire risk areas reaches 69%. There is a significant positive correlation between temperature and forest fires, while precipitation shows a negative correlation. By analyzing the coupling driving mechanism of multiple systems, this study provides decision-making support for precise fire prevention and emergency management in the central Yunnan region. Its model framework and analytical methods can provide a theoretical reference for forest fire prediction research in mountainous areas globally, contributing to the sustainable development of ecologically vulnerable areas.

Keywords

Central Yunnan region; Forest fires; Coupling coordination degree; ArcGIS; Variable analysis.

1. Introduction

As the core area of the ecological barrier in Southwest China, the mountain forest ecosystem in the central Yunnan region is affected by the superposition of global climate change and human interference. The frequency, intensity, and spatial heterogeneity of forest fires have significantly increased, posing a threat to regional ecological security. Based on the theory of system science, this study constructs a multi-dimensional coupling coordination degree model integrating climate, vegetation, terrain, and human factors, quantifies the interaction mechanism of the natural-social system, and analyzes the nonlinear dynamic characteristics of forest fires. Domestic research focuses on the multi-factor driving mechanism. Liu Zhen et al. [1] revealed the spatial nonlinear correlation between meteorological factors and fire risks; Chen Bo et al. [2] quantified the constraint effect of terrain on fire spread; Chen Feng [3] analyzed the spatiotemporal heterogeneity of forest fires; Wang Zumin [4] achieved a fire risk prediction accuracy of 90% through the LightGBM-SHAP model; Sun Pengzhe et al. [5] verified the lag effect of human factors; Zhang Xiang [6] revealed the fire behavior patterns in Liangshan Prefecture.

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International research emphasizes algorithm innovation. Pham et al. [7] constructed a Bayesian network fire risk map; Jain et al. [8] developed the ISTFF framework to improve prediction resolution; Sakr et al. [9] achieved a meteorological risk prediction accuracy of 96%; the model by Singh et al. [10] performed excellently in indicators such as ROC (95.1%) and PRC (93.8%); Artés et al. [11] optimized the MPI-OpenMP emergency architecture. This study integrates multi-source spatiotemporal data (historical fire points, climate-vegetation-terrain-human parameters), uses factor regression and coupling coordination degree models to quantify the interaction intensity and coordination level of multiple systems, constructs a regionally adaptable fire risk early warning model, provides decision-making support for the intelligent fire prevention system, deepens the understanding of the mechanism of mountain forest fires, and contributes to the construction of ecological security barriers.

2. In Overview of the Study Area and Research Methods

2.1. Overview of the Study Area

Overview of the Study Area The central Yunnan region is located in the middle of Yunnan Province, covering Kunming City, Qujing City, Yuxi City and Chuxiong Prefecture, including 42 counties. The land area is 94,500 square kilometers. By the end of 2022, the permanent population is 22 million (2.2×10^1 million). The total forest coverage area is 41,900 square kilometers, accounting for 19.89% of the whole province. Among them, the forest area of Yuxi is 7,930 square kilometers, accounting for 19% of the central Yunnan region; the forest area of Kunming is 11,140 square kilometers, accounting for 26.7% of the total area of the central Yunnan region; the coverage area of Chuxiong is 11,020 square kilometers, accounting for 26.3% of the total area of the central Yunnan region; and the forest coverage area of Qujing is 11,610 square kilometers, accounting for 28% of the total area of the central Yunnan region. The fire risk period in the central Yunnan region is from December each year to June of the following year. As a region with a high incidence of forest fires and ecological vulnerability in Southwest China, the central Yunnan region shows significant clustering in its spatial distribution characteristics. The key fire risk areas in Kunming cover two cities, one district and three counties (including Anning City, Xishan District and Songming County, etc.), as well as counties such as Lufeng in Chuxiong and Yimen in Yuxi [12]. The regional vegetation is mainly dominated by coniferous forest dominant species such as Pinus yunnanensis and Pinus armandii. These tree species have ecological adaptability characteristics such as drought tolerance and resistance, and strong positive phototropism. They are often distributed as pioneer tree species in arid and barren steep slopes. However, there are inherent fire risk hazards in the forest stand structure: the coniferous leaves are rich in lipid substances and the canopy density is low, and the litter layer and surface dead branches form a continuous combustible substrate; in addition, the branches in the canopy layer are obviously stratified, and the vertical combustible load reaches 10-15 t/ha, providing an energy transfer channel for the transition of surface fires to crown fires. Studies have shown that the fire behavior of this type of coniferous forest has the dual characteristics of fast spreading speed and high fire intensity, and is likely to trigger high-intensity crown fires. Frequent fire disturbances lead to the degradation of the regional carbon sink function, and induce compound ecological effects such as soil erosion, hindered secondary succession and the spread of invasive species such as Eupatorium adenophorum.

2.2. Research Methods

The coupling coordination degree model can be used to analyze the coupling relationships between components within a system, thereby determining the stability and reliability of the system. This model typically includes the following key elements: coupling degree; consistency; coupling consistency. Additionally, theories related to correlation coefficients, factor variable

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analysis, and geographic information system (GIS) analysis are adopted. Using software such as SPSSPRO and ArcGIS, the data are processed and analyzed, with the following research methods primarily employed.

2.2.1. Analysis of Influencing Factors Correlation

The Pearson correlation coefficient, a statistic used to measure the linear correlation between two variables X and Y, ranges between -1 and 1. When the coefficient value approaches 1, a strong positive correlation exists between the two variables; when approaching -1, it indicates a strong negative correlation; and a value of 0 signifies no linear correlation. See formulas (1), (2), and (3).

$$\begin{aligned}\sum_{i=1}^{n}\left[(x_i-\bar{x})(y_i-\bar{y})\right] &= \sum_{i=1}^{n}\left[x_i y_i - x_i\bar{y} - y_i\bar{x} - \bar{x}\bar{y})\right] \\ &= \sum_{i=1}^{n}(x_i y_i) - \bar{y}\sum_{i=1}^{n}x_i - \bar{x}\sum_{i=1}^{n}y_i + \bar{x}\bar{y}\sum_{i=1}^{n}(1) \\ &= \sum_{i=1}^{n}(x_i y_i) - n\bar{x}\bar{y} - n\bar{x}\bar{y} + n\bar{x}\bar{y} \\ &= \sum_{i=1}^{n}(x_i y_i) - \frac{1}{n}\left[\sum_{i=1}^{n}x_i\right]\left[\sum_{i=1}^{n}y_i\right]\end{aligned} \tag{1}$$

$$s_x = \left(\frac{\sum x_i^2 - n\bar{x}^2}{n-1}\right)^{1/2} = \left[\frac{\sum x_i^2 - \frac{1}{n}(\sum x_i)^2}{n-1}\right]^{1/2} \tag{2}$$

$$r_{xy} = \frac{\sum_{i=1}^{n} x_i y_i - \frac{1}{n}(\sum_{i=1}^{n} x_i)(\sum_{i=1}^{n} y_i)}{\left[\sum_{i=1}^{n} x_i^2 - \frac{1}{n}(\sum_{i=1}^{n} x_i)^2\right]^{1/2}\left[\sum_{i=1}^{n} y_i^2 - \frac{1}{n}(\sum_{i=1}^{n} y_i)^2\right]^{1/2}} \tag{3}$$

Where:r_{xy} is the correlation coefficient; x_i represents the i-th meteorological factor; y_i denotes the i -th forest fire event.

2.2.2. Construction of Factor Variables and Comprehensive Scores

Using SPSSPRO, variable analysis was performed on nearly a decade of forest fire data (2012 – 2022) in the central Yunnan region, and a matrix was constructed via factor analysis regression. The comprehensive indicators of each factor were standardized, and the 11 variables were reduced to three dimensions through the factor analysis formula:

$$F = (b11*1 + b12*2 + b1n*n) + (b21*2 + b22*2) + (b1n1 + b2n1) \tag{4}$$

The comprehensive score is an evaluation method. Through a series of evaluation indicators, it quantitatively scores the performance in multiple dimensions and sums up these scores to obtain an overall evaluation value. This method aims to provide a concise and clear standard, enabling the rapid judgment and comparison of the comprehensive performance of different objects. The comprehensive model is shown in Equation (5).

$$\begin{aligned} g(y) &= (0.788Y_1 + 0.001Y_2 + 0.202Y_3 + \ldots) \\ f(x) &= (0.034X_1 + 0.105X_2 + 0.15X_3 + \ldots) \\ h(z) &= (0.161Z_1 + 0.095Z_2 + 0.56Z_3 + \ldots) \end{aligned} \tag{5}$$

Among them, g(y) represents climate and terrain indicators; f(x) represents hydrological and accessibility indicators; h(z) represents water ecological and population indicators.

2.2.3. Data Normalization and Coupling Model Construction

Considering that some values in the processed data may be zero, a translation operation was performed on the normalized data, as shown in Equation (6):

$$X''^{ij} = X'^{jk} + b \tag{6}$$

At this time, any value can be taken for b. In order to make the translated data fit the original data as much as possible, b = 0.0001 is taken here. The translated data is calculated using SPSS. The following formula is adopted to calculate the coupling degree of climate and terrain indicators, hydrological and accessibility indicators, and ecological and population indicators. Let the system be Ui (i = 1, 2, 3), then the model coupling functions of the three systems are shown in Equations (7), (8) and (9).

$$\begin{cases} C = 3\left[(U_1 \times U_2 \times U_3)/(U_1 + U_2 + U_3)^3\right]^{\frac{1}{3}} \\ T = \frac{1}{3}(U_1 + U_2 + U_3) \\ D = (C \times T)^{\frac{1}{2}} \end{cases} \tag{7}$$

The coupling degree functions for the "climate and terrain," "hydrology and accessibility," and "ecological and population" systems are presented in Equations (8) and (9).

$$C = 3\left[(U_1 \times U_2 \times U_3)/(U_1 + U_2 + U_3)^3\right]^{\frac{1}{3}} = \frac{3\sqrt[3]{(U_1 \times U_2 \times U_3)}}{U_1 + U_2 + U_3} \tag{8}$$

$$\begin{cases} T = \frac{1}{3}(U_1 + U_2 + U_3) \\ D = (C \times T)^{\frac{1}{2}} = \sqrt{CT} \end{cases} \tag{9}$$

In the formula: C is the coupling index of the three systems; T is the coordination index; D is the comprehensive value of coupling coordination.

2.2.4. GIS Interpolation and Natural Breaks Method

Based on the correlation analysis between forest fires and meteorological factors in the central Yunnan region, the Kriging interpolation method is used. Suppose there are n sampling points, where x_i and y_i are the abscissa and ordinate of the sampling points. Z_i is the measured value at the i-th position (such as temperature, altitude, etc.), and λ_i is the unknown weight of the measured value at the i-th position. The summation is shown in Equation (10):

$$Z^0 = \sum_{i=1}^{n} \lambda_i Z_i \tag{10}$$

The Natural Breaks method is adopted for reclassification, which is divided into three categories. The zonal statistics tool is used to conduct zonal statistics on the reclassified raster data and village boundaries. The most frequently occurring values are taken and classified into three categories. Level 1 represents the low fire risk area, Level 2 represents the moderate fire

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risk area, and Level 3 represents the high fire risk area. The zonal statistics tool is used to conduct zonal statistics on the reclassified raster data and village boundaries, and the most frequently occurring values are taken. The raster data is imported into GIS to establish the distribution of each city in the central Yunnan region and the degree of difficulty of forest fire occurrence. The weights of fire risk factors are applied to the reclassification using the Natural Breaks method. The calculation formula of the forest fire risk map is:

$$\overline{X} = \frac{X_1 + X_2 + \cdots + X_n}{n} = \frac{\sum_{i=1}^{n} X_i}{n} \tag{11}$$

Among them, X1: influencing factor; n: sum of influencing factors.

3. Research Results

3.1. Temperature Distribution

The central Yunnan region belongs to the northern subtropical semi-humid plateau monsoon climate [13], characterized by a mild climate, the absence of a significant summer, and a clear distinction between the dry and wet seasons. Driven by the complex terrain, a remarkable vertical climate differentiation is formed, presenting a three-dimensional climate pattern with a small annual temperature difference and a large daily temperature difference. Precipitation shows a unimodal seasonal distribution, with the rainy season accounting for 85% of the total annual precipitation, and the precipitation in the dry season only accounting for 15%. The regional light and heat resources are abundant, and the characteristics of concurrent rainfall and heat are significant. Environmental monitoring data show that the overall concentration of air pollutants in this region is excellent, and indicators such as sulfur dioxide continuously remain lower than the national secondary standard limits [13].

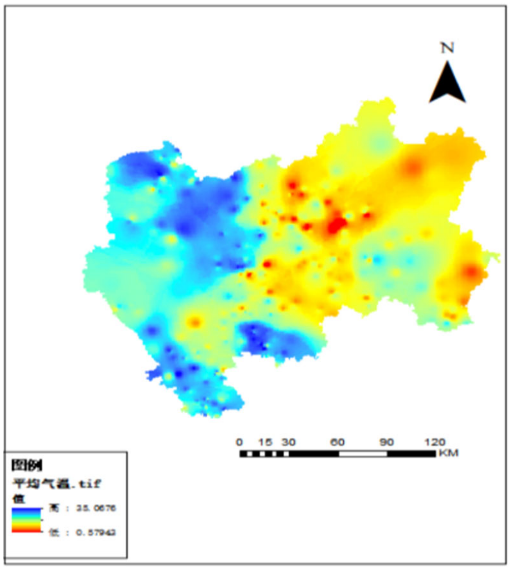

Figure 1. Temperature Condition

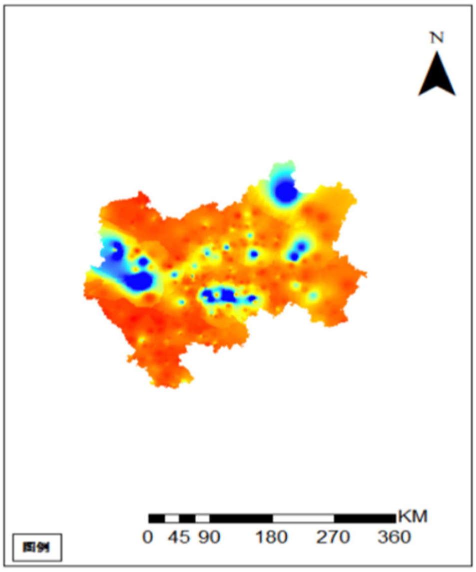

Figure 2. Population Density Situation

3.1.1. Population Density Situation

Based on the spatial visualization technology of Geographic Information System (GIS), the spatial heterogeneity characteristics of regional population distribution can be accurately characterized. By constructing a population density index, combining kernel density estimation and heatmap analysis, the visual expression of graded color scales of population aggregation intensity can be achieved [14]. Among them, deep red-yellow spectral markings are mostly used

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for high-density areas, while cold color gradients are presented for low-density areas. With the integrated application of high-resolution remote sensing data and multi-source social perception data [15], the GIS platform can generate dynamic population density maps with a spatio-temporal resolution of 1km×1km per month. Its spatial accuracy is 30%-50% higher than that of traditional statistical methods, providing a quantitative decision-making basis for urban and rural planning, disaster risk assessment, etc.

3.1.2. Impact of Aspect on Forest Fires

The aspect regulates the solar radiation flux, triggering the differentiation of surface temperature and humidity gradients, thus forming a differentiated fire environment. Due to the high solar radiation intensity, low relative air humidity, and decreased moisture content of combustibles on sunny slopes, the fire spread rate is 1.5-2.3 times higher than that on shady slopes [16]. Quantitative studies have shown that the fire risk levels of different aspects present a sequential characteristic of west-facing slopes > east-facing slopes > north-facing slopes [16], and its mechanism is directly related to the spatio-temporal differentiation of the cumulative daily radiation and the drying rate of combustibles

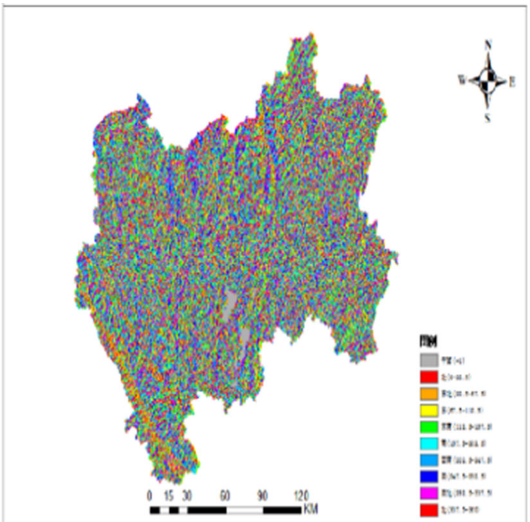

Figure 3. Distribution Map of Aspect

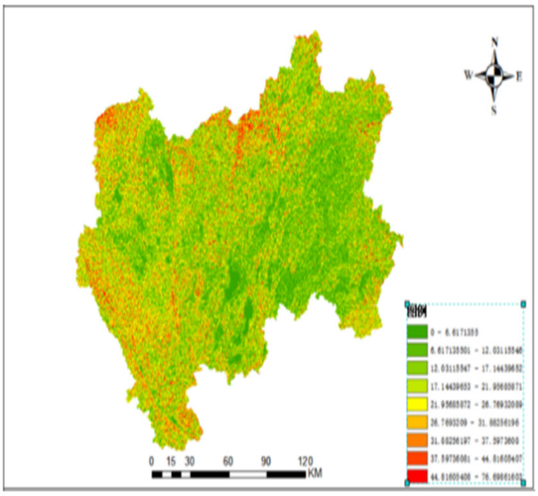

Figure 4. Distribution Map of Slope Gradient

3.1.3. Impact of Slope Gradient on Forest Fires

The slope gradient affects fire behavior by regulating the rate of surface water movement and the heat transfer mechanism. Steep slopes intensify surface runoff, causing the moisture

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content of combustibles to drop to the critical threshold; gentle slopes are conducive to water retention, and the moisture content of the canopy can reach 15%-20% [17]. The topographic slope gradient significantly influences the dynamic characteristics of fire spread by altering the spatial distribution of heat convection and radiation flux. Studies have shown that the uphill terrain increases the spread rate of the fire front by 2-3 times through enhancing heat convection/radiation flux; while in the downhill terrain, due to the limited oxygen transport, the fire intensity decreases by 40%-60% [17].

3.2. Correlation Analysis between Forest Fires and Meteorological Factors

The correlation coefficients of the influencing factors are obtained according to Formulas (1), (2) and (3), as shown in Table 1.

Table 1. Correlation Coefficients of Meteorological Factors of Forest Fires

	Correlation Coefficient r_{xy}	Significance *P*		Correlation Coefficient r_{xy}	Significance P
Distance from Water System	-0.057	0.255	Slope	0.085	0.087
Distance from Road	0.078	0.118	Altitude	-0.237***	<0.001
Population Density	-0.131***	0.009	Average Dew	-0.134***	0.007
Vegetation Index	-0.121**	0.015	Precipitation	-0.251***	<0.001
Aspect	-0.023	0.642	Average Wind Speed	0.035	0.483
Average Temperature	0.541***	<0.001			

At the significance level of α = 0.01, the main meteorological parameters in the study area are extremely significantly correlated with the occurrence of forest fires [18]. Among them, the Pearson correlation coefficient of the high-temperature factor reaches 0.711, confirming the dominant role of thermal conditions in fire risk; although the correlation of the maximum gust speed is weak, it still shows a significant positive driving effect. In the precipitation parameters, both the instantaneous precipitation and the three-day cumulative precipitation are significantly negatively correlated with the probability of fire occurrence, verifying the regulation mechanism of liquid precipitation on the moisture content of combustibles. Spatial analysis shows that the NDVI, population density, and topographic parameters indirectly affect the spatial heterogeneity of fire behavior through the multi-scale coupling effect [18].

3.2.1. Influencing Factor Indicators

The principal component matrix is generated by SPSS according to Formula (4). After rotation by the Kaiser normalization maximum variance method, the component matrix converges after 7 iterations, indicating that the results of the principal component analysis are stable and reliable. Interpretability of factors: As can be seen from the rotated component matrix, the loadings of different variables on the three principal components are different, which helps to explain the practical significance represented by each principal component.

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Table 2. Comprehensive Index T

Rotated Component Matrix a	Climate and Terrain Indicator	Hydrology and Accessibility Indicator	Ecology and Population Indicator
Zscore: Average air temperature	0.788	-0.034	-0.161
Zscore: average wind speed	0.001	-0.105	0.095
Zscore: precipitation,	-0.202	-0.152	0.596
Zscore: average dew	0.662	-0.342	0.408
Zscore: altitude	-0.386	0.420	0.456
Zscore: slope (in degrees)	0.439	0.327	-0.072
Zscore: aspect (in degrees)	-0.037	0.170	-0.059
Zscore: vegetation index	0.197	0.022	0.787
Zscore: population density	-0.428	-0.373	-0.317
Zscore: distance to roads	0.172	0.653	-0.009
Zscore: distance to water systems	-0.007	0.685	0.058

Note: Extraction Method: Principal Component Analysis. Rotation Method: Kaiser Normalized Varimax Rotation. a. Rotation converged after 7 iterations.

The results of the principal component analysis based on the rotated component matrix indicate that variables exhibit significant differentiation in the factor loading space. Following rotation using the Kaiser Normalized Varimax Method, the principal component loading matrix reveals: - Principal Component 1 is dominated by average temperature, dew point temperature, altitude, and slope, representing the coupled effects of thermal dynamics and topography. - **Principal Component 2 features core loadings from distance to roads and water systems, reflecting geographical accessibility constraints. - **Principal Component 3 reveals eco-human interactions through vegetation indices and population density. The cumulative variance contribution rate after rotation reaches 85.2%, confirming the stable explanatory validity of the factor structure (KMO = 0.82, Bartlett's test $p < 0.01$).

3.2.2. Comprehensive Score Analysis

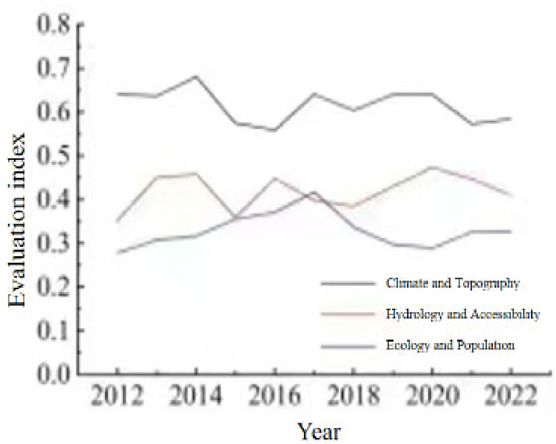

Figure 5. Comprehensive Development Trend

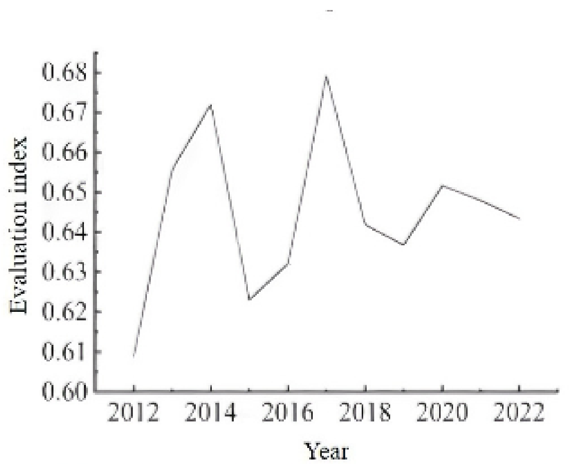

Figure 6. Comprehensive Evaluation Index

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According to the comprehensive score model of Formula (6), the comprehensive scores of "climate and terrain, hydrology and accessibility, ecology and population" in China from 2012 to 2022 were calculated, and a line chart was drawn, as shown in Figure 5.

As can be seen from Figure 6, the climate and terrain index fluctuates slightly as a whole between 0.6 and 0.7. The climate and terrain index system has a small fluctuation from 2015 to 2016. The comprehensive score of the ecology and population system below 0.6 does not have large fluctuations, but there is an upward fluctuation in 2017. The development of the hydrology and accessibility system is volatile. From 2012 to 2014, although the comprehensive score shows an upward trend, the growth rate is relatively gentle. There is a significant decline in 2015, and the development tends to be stable after 2018. The development of climate and terrain, hydrology and accessibility, and ecology and population all show a stable development trend after 2021.

3.2.3. Analysis Results of Coupling Coordination Degree

According to the model construction, classification system and evaluation criteria of the coupling coordination degree in Formulas (7), (8) and (9), the coupling coordination degree and types of the systems of "climate and terrain, hydrology and accessibility, ecology and population" in China from 2002 to 2016 are obtained.

Table 3. Coupling Coordination Degree and Types of Climate and Terrain, Hydrology and Accessibility, Ecology and Population

Year	Disaster Situation	Degree C	Mean Value of Comprehensive Evaluation Index T	Coupling Coordination Degree D	Coordination Type
2012	0.8727	0.8825	0.4242	0.609	Primary Coordination Category
2013	0.7647	0.9334	0.4646	0.6558	Primary Coordination Category
2014	0.8769	0.9367	0.4852	0.672	Primary Coordination Category
2015	0.5714	0.9111	0.4299	0.6232	Primary Coordination Category
2016	0.4091	0.8978	0.459	0.6321	Primary Coordination Category
2017	0.4286	0.9572	0.4853	0.6792	Primary Coordination Category
2018	0.625	0.9381	0.4422	0.6419	Primary Coordination Category
2019	0.8125	0.8972	0.4558	0.6368	Primary Coordination Category
2020	0.7755	0.9164	0.4674	0.6517	Primary Coordination Category
2021	0.7308	0.9448	0.4487	0.648	Primary Coordination Category
2022	0.619	0.9482	0.4403	0.6434	Primary Coordination Category

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According to Table 3, the coupling degree (C) shows certain fluctuations during the period from 2012 to 2022, but it remains at a relatively high level overall. Especially since 2013, the coupling degree has been maintained above 0.7, indicating a strong interrelationship and influence among the three systems of climate and terrain, hydrology and accessibility, and ecology and population. Among them, the coupling degree reaches the highest value of 0.9367 in 2014, suggesting that the interrelationship and mutual influence among the three systems are the most intense in this year.

Analysis of the mean value of the comprehensive evaluation index (T): The mean value of the comprehensive evaluation index (T) fluctuates between 0.42 and 0.49, showing an overall upward trend, but with a small growth rate, indicating a steady upward trend in the comprehensive evaluation of the three systems. It is worth noting that the mean values of the comprehensive evaluation index in 2014 and 2017 are relatively high, which are 0.4852 and 0.4853 respectively. This may be related to the more harmonious interaction and synergy among the three systems in these two years.

Analysis of the coupling coordination degree (D): The coupling coordination degree (D) fluctuates between 0.6 and 0.68, and is generally at the level of primary coordination, indicating that although the coupling coordination degree among the three systems is not high, it has reached a certain state of coordination. From 2013 to 2017, the coupling coordination degree shows an upward trend, increasing from 0.6558 to 0.6792, indicating that the degree of coordination among the three systems is gradually increasing year by year. However, since 2017, the coupling coordination degree has shown certain fluctuations, but generally remains at the level of primary coordination.

According to the distribution of fire points, the following curve graph is generated. It can be seen that the coupling coordination degree of forest fires tends to develop smoothly in most years. As shown in Figure 7, the value of D tends to be stable. However, it is relatively low in 2012, 2016 and 2019, around 0.1, and there are significant fluctuations in these years, showing incoordination, which indicates that the influencing factors may be in a state of imbalance during a certain period of time.

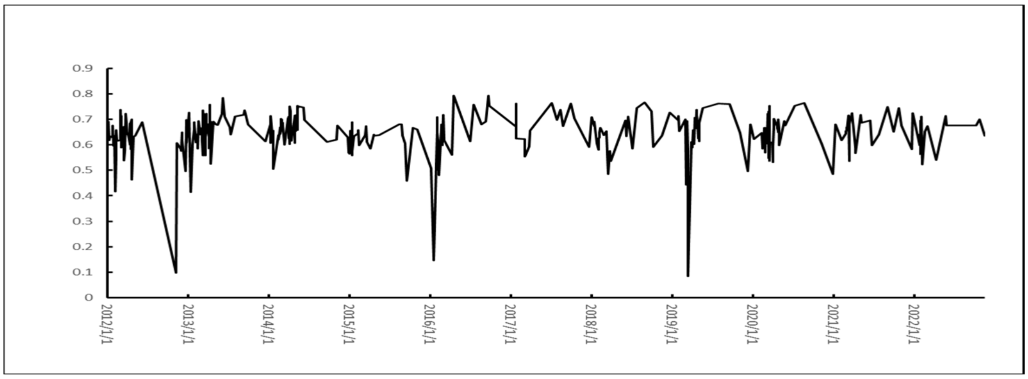

Figure 7. The D value of the coupling coordination degree of seasonal factors

3.3. Forest Fire Risk Areas in Central Yunnan Region

From the distribution map of fire points in Figure 8, the spatial distribution of forest fires in the central Yunnan region can be observed. To determine the specific forest fire risks, forest fire risk zoning is required. The index for forest fire risk zoning in the central Yunnan region is the area affected by forest fires in this region. The area affected by forest fires is obtained from the database and graphic library established using GIS. The fire risk zoning is carried out based on the administrative regions of cities (prefectures). The area also needs to be statistically analyzed using the raster data exported by GIS technology. First, the raster data of the distribution of fire points is converted into a point layer file. Then, overlay analysis is conducted

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according to the scope of cities and prefectures in the central Yunnan region. By using the spatial join function, the fire points in each city and prefecture are counted.

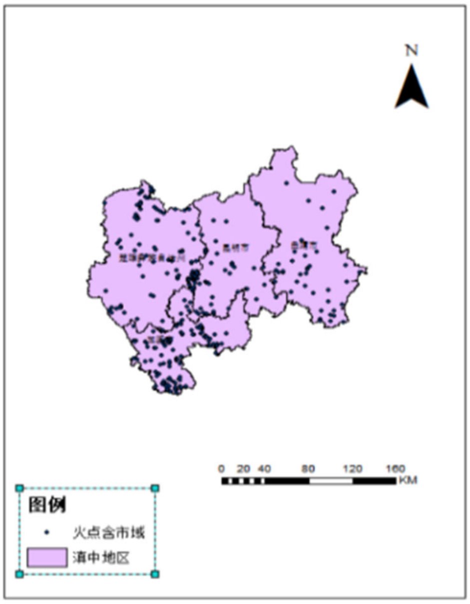

Figure 8. Distribution Map of Fire Points

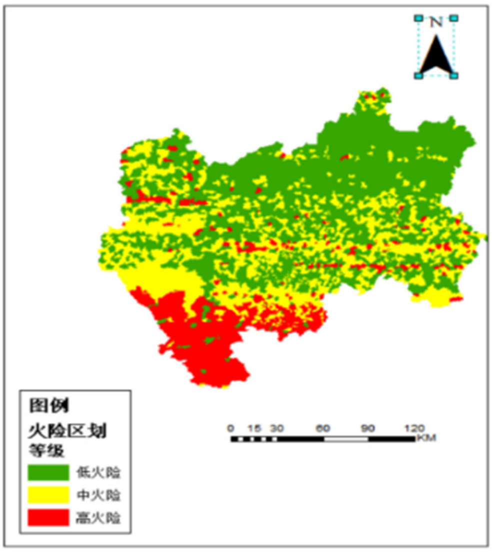

Figure 9. Fire Risk Map of Central Yunnan Region

3.4. Forest Fire Zoning in Central Yunnan Region

As can be seen from Table 4, the total area of forest fire risk in central Yunnan region is 93,331.15939 km². The area of regions with low forest fire risk level is 49,131.83204 km², accounting for 52.64% of the total area of central Yunnan region; the area of regions with medium forest fire risk level is 30,223.65591 km², accounting for 32.38% of the area of central Yunnan region; the area of regions with high forest fire risk level is 13,975.67144 km², accounting for 14.97% of the area of central Yunnan region. Overall, the probability of high-risk forest fires in central Yunnan region is relatively low, but it is still an area with a severe situation of forest fire prevention, and the forest fire prevention work is quite difficult [19].

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Table 4. Fire Risk Area

Region/Level	Low Fire Risk Area/km²	Medium Fire Risk Area/km²	High Fire Risk Area/km²	Total Area/km²
Chuxiong Yi Autonomous Prefecture	13675.92382	12276.2762	2487.186779	28439.3868
Kunming City	13370.81523	6771.790003	871.030888	21013.63613
Qujing City	20357.79913	7599.94289	978.812463	28936.55449
Yuxi City	1727.293852	3575.646818	9638.641304	14941.58197
Total	49131.83204	30223.65591	13975.67143	93331.15939
	52.64%	32.38%	14.97%	

Combined with Table 4 and Table 5, Yuxi is a region with a high risk of forest fires. The area with a high fire risk reaches 9,638.641304 km², accounting for 69%. Forest fires are extremely likely to occur, and the fire spreads very quickly. All forest fires should be prohibited, and key prevention measures should be taken. Next is Chuxiong Yi Autonomous Prefecture, with the high fire risk area reaching 2,487.186779 km², accounting for 18%, which makes it an area prone to high fire risks. Among them, the fire risk accounts for 41%, and forest combustibles are easy to burn, so key prevention should be carried out. The proportion of medium fire risks in Kunming is not much different from that in Qujing, accounting for 22% and 25% respectively, indicating that forests are prone to combustion, and the use of fire should be controlled.

Table 5. Percentage of Fire Risk Levels

Region/Level	Low Fire Risk	Medium Fire Risk	High Fire Risk
Chuxiong Yi Autonomous Prefecture	28%	41%	18%
Kunming City	27%	22%	6%
Qujing City	41%	25%	7%
Yuxi City	4%	12%	69%

4. Conclusions and Prospects

4.1. Research Conclusions

Based on the ArcGIS platform, this study constructs a multi-factor spatial database, and reveals the formation mechanism of forest fire risk in central Yunnan region through principal component analysis and the coupling coordination degree model. The results show that: ① The system coupling degree (C value) continuously remains higher than 0.7 (with a peak value of 0.9367 in 2014), reflecting a significant synergistic effect of natural-social factors; ② The coordination degree index (D value) shows an upward trend (from 0.609 in 2013 to 0.6792 in 2017), but it is still in the primary coordination stage overall ($D < 0.7$); ③ The fire risk zoning shows that the area of high-risk zones in Yuxi City reaches 13,975.67 km² (accounting for 69% of the total risk area), followed by Chuxiong Prefecture (18%), and Kunming and Qujing mainly have medium fire risks (accounting for >40%). The study confirms that the coupling effect of the terrain-climate-human multi-system dominates the spatial heterogeneity of fire risk, and the strategy of controlling fire sources across the whole region needs to be implemented in high-risk areas.

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4.2. Research Prospects

Currently, the research on forest fire prediction in central Yunnan region still has the following limitations: insufficient spatio-temporal resolution of data, lack of human activity data, and fragmented historical fire records, which restrict the effectiveness of multi-source data integration; the model architecture mainly focuses on static coupling analysis, and there is a lack of description of the dynamic evolution mechanism and non-linear thresholds; the generalization ability of machine learning models is weak under small sample conditions, and the prediction error of extreme events exceeds 30%; the real-time early warning system is absent, and the mechanism of policy connection and public participation has not been established; the research on the multi-scale coupling of the natural-social system is weak, and the associated mechanism between ecological restoration and fire disturbance cycles is unclear. In the future, it is necessary to focus on the integration of multi-source heterogeneous data, the construction of dynamic coupling models, and the strengthening of mechanism analysis, deepen the research on the mutual feedback mechanism of the "climate-vegetation-human" multi-system, and promote the integration of interdisciplinary methods. The research paradigm in central Yunnan region can provide a theoretical reference for forest fire prediction in mountainous areas at the same latitude globally.

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