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Original Research

Landscape Ecological Risk Assessment and Evaluation of Influencing Factors of Jinsha River Basin in Yunnan Province Based on Land Use/Cover Change

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Abstract

The ecological quality of the Jinsha River Basin in Yunnan Province has been declining due to human activities and global climate change. Thus, conducting a comprehensive landscape ecological risk assessment is essential for reconciling ecological protection with economic development and fostering sustainable regional growth. This study analyzes land-use and cover change data to evaluate the landscape ecological risk in the Jinsha River Basin from 1985 to 2020. By calculating landscape pattern indices and utilizing GIS technology to create a landscape risk index model, we further investigate the spatiotemporal evolution patterns and influencing factors of ecological risk in the area. The results reveal that: (1) Between 1985 and 2020, the primary landscape types in the Jinsha River Basin were cultivated land, forest land, and grassland, collectively accounting for approximately 98% of the total area. Notably, built-up land has increased continuously while grassland has decreased. (2) The assessment indicates that the region predominantly experiences moderate, relatively high, and high ecological risks, comprising over 80% of the area, with moderate and relatively high risks being the most significant. High ecological risk areas are primarily concentrated in Kunming City and Qujing City. (3) The global Moran's I value consistently exceeds 0.2 and exhibits a downward trend, indicating a distribution of landscape ecological risk that is "high in the center, low at the edges," with local spatial autocorrelation characterized by "high-high" (H-H) and "low-low" (L-L) clusters. (4) Controlling for annual average precipitation reveals a positive correlation between annual average temperature and ecological risk while controlling for temperature shows a negative correlation between annual average

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precipitation and ecological risk. The findings of this study provide valuable insights for optimizing land resources and promoting sustainable development in the Jinsha River Basin.

Keywords: land-use/cover change, landscape ecological risk, spatial autocorrelation, influencing factors, Jinsha river basin

Introduction

With the rapid pace of economic development and urbanization, land-use/cover change (LUCC) is accelerating [1], intensifying the conflict between economic growth and ecological protection. Inappropriate land-use practices negatively impact the sustainable development of socio-economic and ecological environmental quality, increasing potential risks to ecosystems, biodiversity, and ecological environments. This results in a range of ecological problems, including environmental degradation, soil erosion, land degradation, biodiversity loss, and inefficient resource utilization, thereby significantly heightening ecological risks and threatening the stability and sustainability of ecosystems [2-4]. Quantitatively analyzing land-use changes and effectively assessing regional ecological security has become essential research focuses in the context of global climate change and intensified human activities.

Ecological risk pertains to the probability and extent of adverse changes in ecosystems or ecological processes caused by natural or human-induced factors. It reflects the detrimental impacts of human activities and environmental changes on ecosystems [5], aiding decision-makers in environmental management to understand potential risks better [6]. Ecological risk assessment evaluates the adverse effects of human activities and environmental changes on regional ecosystems [7], providing theoretical support for ecosystem protection and management decisions. Landscape ecological risk assessment, a significant branch of ecological risk assessment, evaluates the negative impacts of disturbances in landscape patterns and ecological processes on the health and functionality of ecosystems. It highlights the scale effects and spatiotemporal heterogeneity of risks [8]. Assessing ecological risk based on landscape patterns of land-use/cover change is vital for evaluating and analyzing land-use's potential risks and impacts on ecosystems. This method adopts a spatial perspective to identify ecological risks within the landscape patterns of land-use/cover change, converting the landscape's spatial structure into spatialized ecological risk variables. This conversion aids in understanding the spatiotemporal changes and spatial heterogeneity of ecological risks [9].

In studies concerning landscape ecological risk, researchers have expanded the spatial scale of their investigations [10, 11] and shifted their focus from land structure to landscape scale [12, 13]. This broader perspective more effectively captures the spatiotemporal heterogeneity of landscapes and allows for a deeper exploration of their driving mechanisms [14, 15]. Such an approach supports the study of regional land dynamics and helps mitigate the ecological risks affecting the environment. The ecological risk assessment of landscape patterns resulting from land-use/cover changes typically employs quantitative analysis methods. By selecting landscape pattern metrics and calculating models, this approach quantifies the impact of land-use on the ecological environment. It comprehensively evaluates the influence of various risk factors on a region. This method addresses the limitations of traditional qualitative analysis, making the assessment results more objective, comprehensive, and accurate. Both domestic and international scholars have recently applied various models and methods to assess landscape ecological risk. Xu et al. [16] utilized the Minimum Cumulative Resistance (MCR) model to develop a landscape ecological risk network model for large mining areas, identifying critical ecological elements and employing complex network methods to analyze the landscape ecological network structure. Ai et al. [17] used semivariogram functions to determine the optimal spatial scale for spatiotemporal beach island landscape ecological risk analysis. Wang et al. [18] enhanced landscape pattern analysis methods by integrating ecosystem service functions into the assessment framework, based on the landscape ecological risk source model, to conduct landscape ecological risk assessment. Chen et al. [19] employed the PSR model and projection pursuit method to examine the characteristics of landscape ecological risk changes. Zhang et al. [20], Wang et al. [21], and Du et al. [22] by calculating landscape pattern indices, developed ecological risk assessment models to analyze and evaluate the spatiotemporal distribution characteristics of landscape ecological risk in China's coastal cities, the Tarim River Basin and the Yellow River Basin, respectively. These studies have achieved notable results, indicating that constructing ecological risk models using landscape pattern indices is a scientifically valid method. According to existing studies, researchers have applied various methods to evaluate landscape ecological risk, yielding commendable results. However, within Yunnan Province, the focus of landscape ecological risk assessments has primarily been restricted to a few small lake basins [23]. Research on larger river basins, such as the Jinsha River, is limited, and most studies primarily assess ecological risks without evaluating the influencing factors [24]. Additionally, most research has been concentrated after 2000 [25], with intervals generally set at ten years. The lack of studies before 2000 and the absence of long-term, shortinterval investigations on landscape ecological risk hinder a thorough understanding of its spatiotemporal evolution and subsequent dynamic monitoring.

Based on the above analysis, this study selects the Jinsha River Basin research area in Yunnan Province, characterized by significant land-use/cover changes, a fragile ecological environment, and prominent ecological risks over the past 35 years. We used multi-period land-use data to establish an evaluation system for landscape ecological risk in the Jinsha River Basin from 1985 to 2020. Through GIS spatial analysis and statistical methods, we conduct a grid-scale analysis of land-use/cover changes and evaluate the spatial differentiation characteristics of landscape ecological risk. Furthermore, we explore the factors influencing landscape ecological risk to obtain comprehensive and accurate evaluation results for the study area. This research aims to fill the gap in studies related to landscape pattern ecological risk assessment due to land-use/cover changes in this region and to provide reference and decision support for the rational utilization of land resources, ecological risk early warning, and prevention and control in the Jinsha River Basin of Yunnan Province.

Material and Methods

Study Area

The Jinsha River Basin is in southwestern China, primarily flowing through Qinghai, Tibet, Sichuan, and Yunnan provinces (Fig. 1). Within Yunnan Province, the river extends for 1560 km, passing through several prefectures and cities, including Diqing Tibetan Autonomous Prefecture, Dali Bai Autonomous Prefecture, Lijiang City, Chuxiong Yi Autonomous Prefecture, Kunming City, Qujing City, and Zhaotong City, covering nearly one-third of Yunnan's land area. By the end of 2020, the population in this region was approximately 26.72 million, making it a core area for economic development in Yunnan Province. The basin features complex terrain dominated by mountains and plateaus, with significant elevation variations and a diverse climate classified as subtropical monsoon. The Jinsha River, a major tributary of the Yangtze River, is characterized by abundant water flow and rapid currents and hosts several large hydropower stations. From 1985 to 2020, rapid economic development and population growth were marked in the Jinsha River Basin of Yunnan Province. This development and utilization of the basin led to issues such as soil erosion and a decline in biodiversity. Therefore, long-term landscape ecological risk assessments of land-use in the Jinsha River Basin are crucial for protecting the ecological

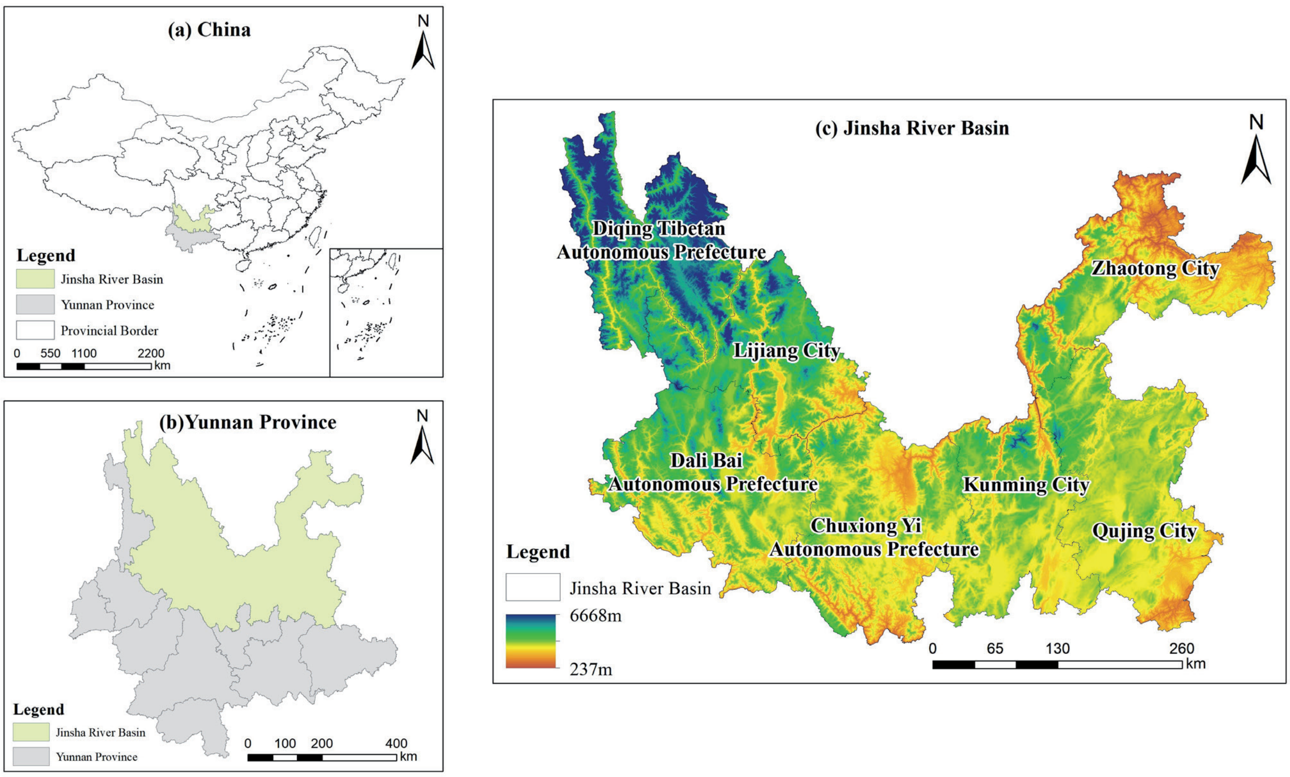

Fig. 1. (a) Position of the province containing the study area in China, map approval number: GS(2019)1822, (b) position of the study area within Yunnan Province, (c) elevation distribution within the study area.

environment and the region's sustainable economic development.

Data Sources

This study utilized land-use data from the Resource and Environment Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/) [26], with a spatial resolution of 1 km. Land-use data from 1985 to 2010 were interpreted using Landsat-TM/ETM remote sensing images, and data for 2015 and 2020 were obtained from Landsat 8 remote sensing images. The land-use types were classified into arable land, forest land, grassland, water bodies, construction land, and unused land based on resource and utilization attributes. The Albers equal-area conic projection was used, and the final comprehensive evaluation accuracy of land-use exceeded 93% [27], meeting the precision requirements of the study area. The annual average precipitation and temperature data from 1985 to 2020 were downloaded from Google Earth Engine (https://code.earthengine.google.com/), with a spatial resolution of 1 km. Land-use data is primarily employed to analyze land-use changes, landscape pattern indices, and landscape ecological risk. In contrast, annual average precipitation and temperature data mainly examine the factors influencing landscape ecological risk.

Research Methods

This paper analyzes the spatiotemporal patterns of land-use changes in the Jinsha River Basin of Yunnan Province from 1985 to 2020 through indicators such as land-use dynamic degree and land-use transition matrix. A GIS grid analysis method is utilized to develop a landscape ecological risk assessment model that comprehensively evaluates the landscape ecological risks in the Jinsha River Basin. Spatial autocorrelation and other techniques are employed to examine the spatial clustering characteristics and trends of landscape ecological risks in the study area. Moreover, partial correlation methods are used to investigate the effects of precipitation and temperature on the landscape ecological risks in this region. The technical roadmap of the study is illustrated in Fig. 2.

Single Land-Use Dynamic Degree

The single land-use dynamic degree refers to the changes or shifts in land-use types within a specific area over a certain period. It is a crucial indicator for measuring the speed and extent of land-use changes [28, 29]. This metric is typically used to assess and monitor the trends and intensity of land-use changes. A higher value indicates more incredible land-use changes in the region.

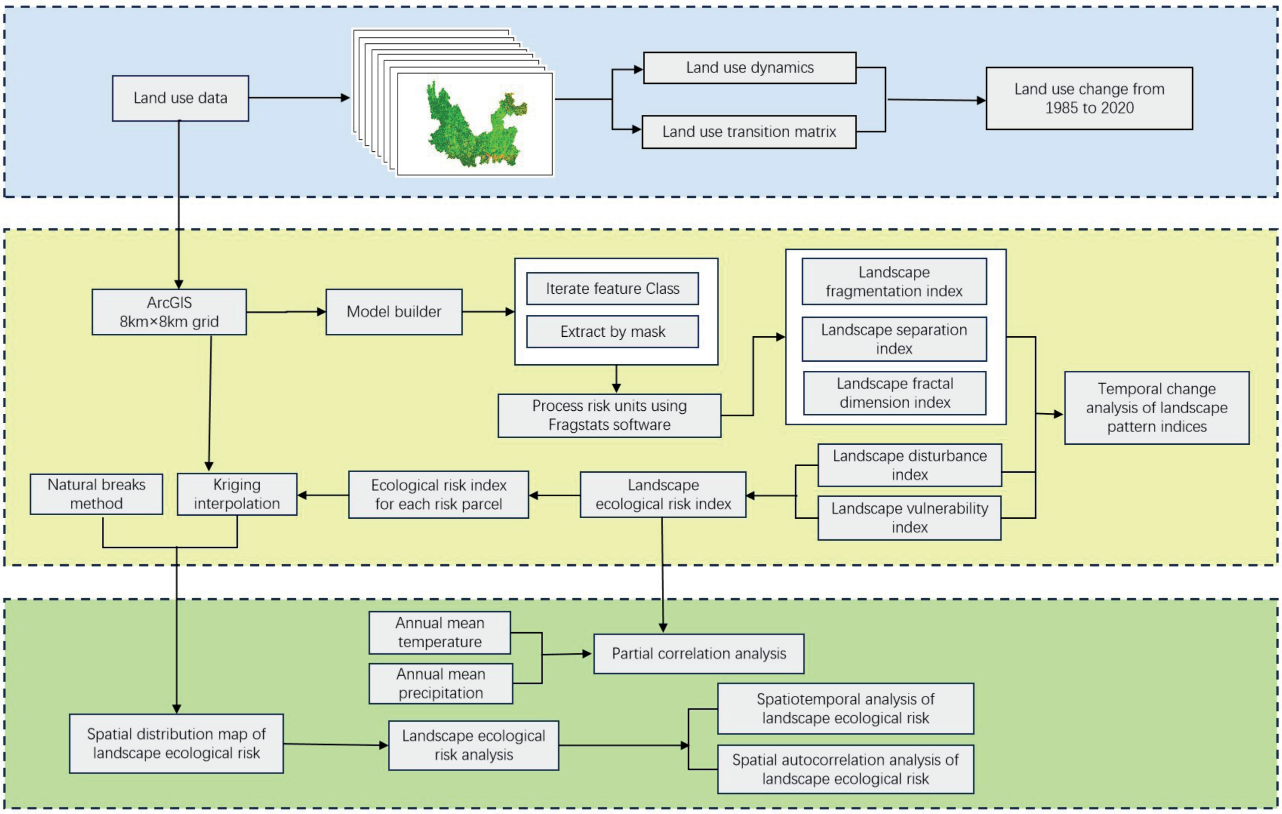

Fig. 2. Methodological Framework of the Study.

$$K = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\%$$

In this context, K signifies the dynamic degree of a particular land-use type over the study period, U_a and U_b represent the land-use areas at the start and end of the study period, respectively, and T refers to the length of the study period.

Land-Use Transition Matrix

The land-use transition matrix is a tool used to describe and analyze the conversion relationships between different land-use types. It reflects the dynamic process of mutual transformation among various land-use types at the beginning and end of a specific period within the study area [30-32]. This matrix provides a clear visualization of the changes in various land-use types over a particular time frame. The formula is:

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ S_{n1} & S_{n2} & \cdots & S_{nn} \end{bmatrix}$$

Within the formula, S_{ij} signifies the area change of a particular land-use type from the initial to the final period of the study. The indices i and j refer to the land-use types at the start and end of the study period, respectively. The term n indicates the number of different land-use types.

Division of Evaluation Units

This study constructs an ecological risk assessment model for the Jinsha River Basin in Yunnan Province from a landscape ecology perspective. Initially, using Fragstats 4.2 software, we calculated three indicators from the land-use data of eight periods between 1985 and 2020: total area (CA), number of patches (NP), and perimeter (PERM) for each landscape. Subsequently, employing landscape ecology methods, we selected indices of landscape fragmentation, isolation, fractal dimension, disturbance, vulnerability, and loss as risk assessment indicators. These were used to construct the Landscape Ecological Risk Index (ERI), ultimately revealing the spatial differentiation and pattern changes of landscape ecological risk in the Jinsha River Basin of Yunnan Province. Referencing the national grid GIS standard "Geographical Grid" (GB 12409-2009) and previous research, the grid size should be sampled based on the principle of 2 to 5 times the average patch area [33, 34]. After comparing the scales of 5 km, 8 km, and 10 km and considering the study area's extent and patch size, we ultimately used the fishnet creation tool in ArcGIS 10.7 to divide the Jinsha River Basin in Yunnan Province into 8 km × 8 km grid units. Using the clipping function, the fishnet was then trimmed, resulting in 4026 evaluation units.

Index of Landscape Ecological Risk

By utilizing the initial parameters and the landscape ecological safety index calculation formula, the ecological risk index for each evaluation unit was computed. The obtained risk index was then used as the parameter value for the center point of each grid cell. The Kriging interpolation method was subsequently applied to visualize the spatial distribution of ecological risk throughout the Jinsha River Basin in Yunnan Province. The landscape ecological risk can be calculated using the following formula [35-37]:

$$ERI = \sum_{i=1}^{n} \frac{A_{ki}}{A_k} R_i$$

Here, n indicates the number of landscape types, A_{ki} represents the area of landscape type i within the k-th risk unit, A_k denotes the area of the k-th risk unit, and Ri signifies the loss index of landscape type i. The construction and calculation process of the ecological risk index are detailed in Table 1.

Analysis of Spatial Autocorrelation

Spatial autocorrelation analysis is a crucial method in spatial statistics, utilized to measure and evaluate the spatial distribution patterns and interrelationships of specific attributes within geographic data. The global Moran's I index tests whether the attribute values of risk assessment units in neighboring or nearby regions are correlated [38]. Its values range from 1 to -1. A Moran's I value greater than 0 indicates a positive correlation, suggesting a clustered distribution on a global scale. A value less than 0 indicates a negative correlation, suggesting a dispersed distribution on a global scale. A value of 0 indicates no correlation, suggesting a random distribution on a global scale [39]. The Local Indicators of Spatial Association (LISA) index provides a detailed description of the local spatial clustering of extreme values of spatial variables, encompassing four types: LL (low-low clustering), HH (high-high clustering), HL (low surrounded by high clustering), and LH (high surrounded by low clustering). The formulas for the global Moran's I and LISA indices are as follows [40]:

$$Moran's I = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{S^2 \sum_{i=1}^{n} \sum_{j=1}^{m} W_j}$$

Table 1. Calculation Process of Landscape Pattern Index.

Index of Landscape Pattern	Formula for Calculation	Meaning of Parameters
Landscape fragmentation Ci	$C_i = \frac{n_i}{A_i}$	In this equation, Ai is the area of landscape type i, and ni is the number of patches. Ci represents the fragmentation degree of the landscape, with higher values indicating lower landscape stability [55].
Degree of landscape isolation Ni	$N_\mathrm{i} = \frac{A}{2A_i}\sqrt{\frac{n_i}{A_i}}$	Within the formula, A denotes the total area of the landscape. Ni measures the degree of separation; higher values indicate a more intricate spatial distribution of the landscape [56].
Landscape fractal dimension Fi	$F_i = 2\ln(p_i/4)/\ln\ A_i$	In the equation, pi represents the perimeter of landscape type i. Fi indicates the fractal dimension of the distribution of individual elements within a specific landscape type [57].
Landscape disturbance Ui	$U_i = aC_i + bN_i + cF_i$	Within the formula, b, and c are the weights assigned to the respective landscape indices, satisfying a+b+c=1, with a=0.5, b=0.3, and c=0.2 [58]. Ui denotes the extent of ecosystem disturbance, where higher values signify a greater influence of human interference on that landscape type.
Landscape vulnerability Ei	Using the expert scoring method, values were assigned to six landscape types and subsequently normalized to produce the final landscape vulnerability index [59, 60], as presented in Table 2.	Ei measures the ability to withstand external disturbances. Larger values imply a diminished capacity to resist external interference, resulting in higher ecological risk.
Landscape loss Ri	$R_i = \sqrt{U_i \times E_i}$	Ri denotes the integrated index of landscape disturbance and vulnerability [61].

Table 2. Value Assignment for Landscape Vulnerability.

Type	Types of Landscapes	Vulnerability Index	Normalized Coefficients
1	arable land	4	0.19
2	forest land	2	0.10
3	grassland	3	0.14
4	water bodies	5	0.24
5	construction land	1	0.05
6	unutilized land	6	0.29

$$LISA = \left(\frac{x_i - \bar{x}}{m}\right)\sum_{i=1}^{n} W_j\,(x_i - \bar{x})$$

In this equation, x_i and x_j are the observed values of a specific attribute for spatial units *x* or *j*, respectively. W_{ij} indicates the spatial weight, $\bar{x}$ is the variable's mean, and S^2 is the variance.

Analysis of Partial Correlation

Partial correlation analysis is a statistical method used to measure the linear relationship between two variables while controlling for the influence of other variables. To better explore the relationship between climate and landscape ecological risk values, this study calculates the partial correlation between landscape ecological risk values and climate factors, as shown in the following formula [41]:

$$r_{-z} = \frac{r_{xy} - r_{xz} \times r_{yz}}{\sqrt{1 - r^2_{xz}} \times \sqrt{1 - r^2_{yz}}}$$

r_{-z} indicates the partial correlation coefficient between variables *x* and *y* with z as the control variable. r_{xy}, r_{xz}, and r_{yz} represent the relationships between *x* and *y*, *x* and z, and *y* and z, respectively.

Results and Discussion

Results

Analysis of Land-Use Changes in the Jinsha River Basin of Yunnan Province

In this section, land-use raster data and the land-use dynamics approach are utilized to determine the area of each land-use category and analyze land-use dynamics. Between 1985 and 2020, cropland, forest land, and grassland were the most widespread land-use types in the Jinsha River Basin of Yunnan Province. Forest land was

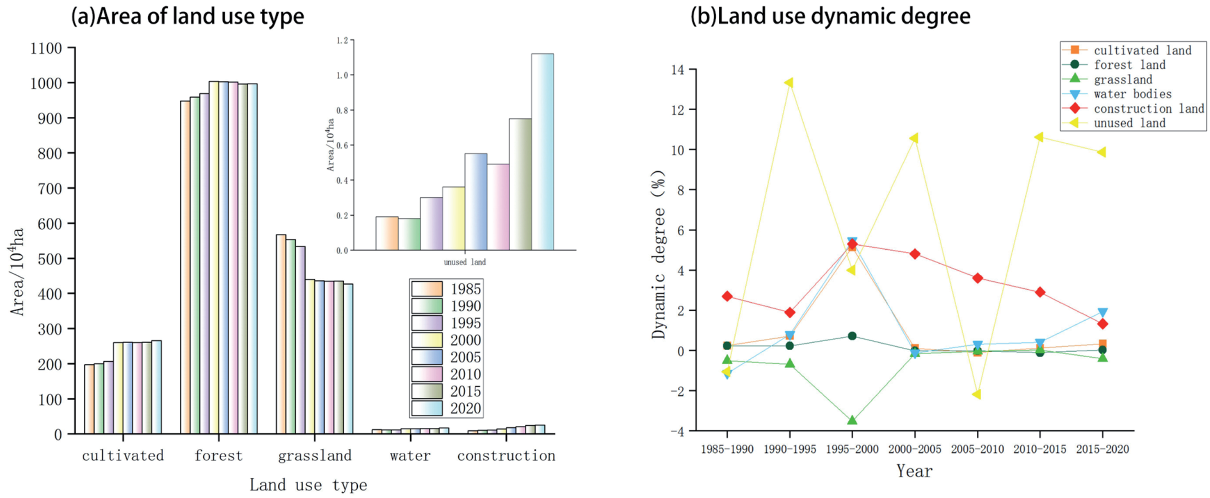

Fig. 3. Area and dynamic degree of various land-use types in the Jinsha River Basin of Yunnan Province from 1985 to 2020.

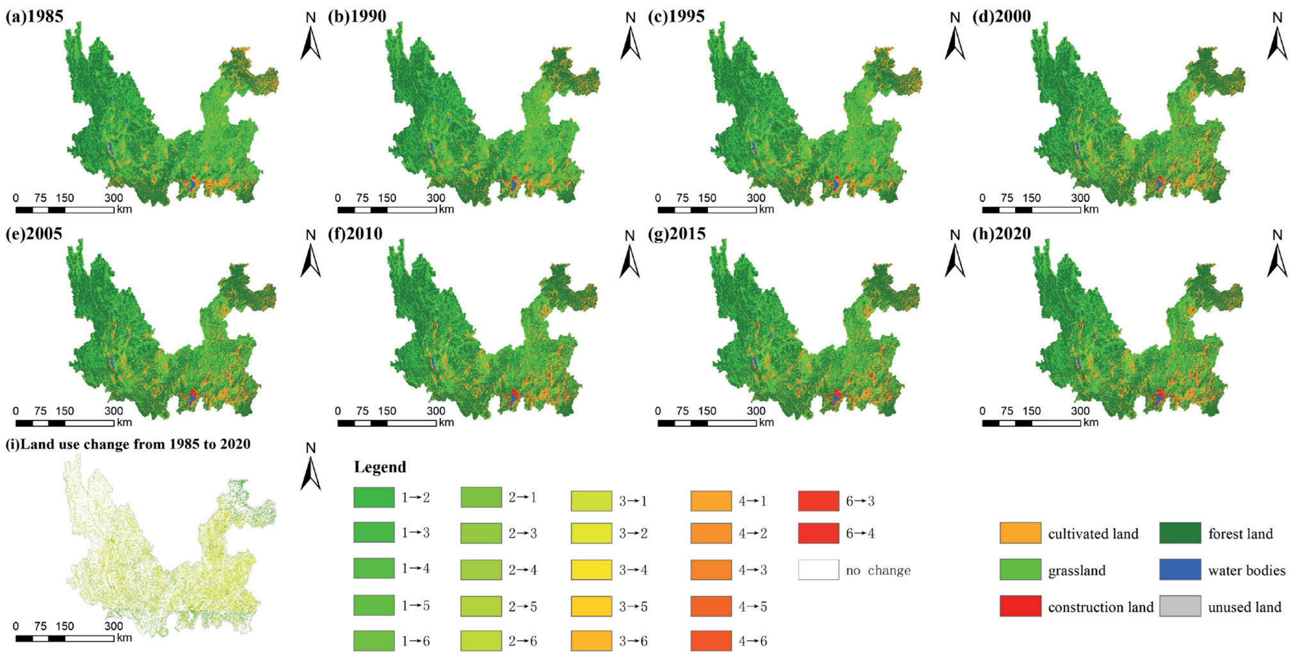

Fig. 4. Land cover map of the Jinsha River Basin in Yunnan Province from 1985 to 2020 (Note: 1 denotes cropland, 2 denotes forest land, 3 denotes grassland, 4 denotes water bodies, 5 denotes construction land, 6 denotes unused land, and → shows the direction of land-use type conversion).

the dominant type, covering more than 54% of the study area. Grassland accounted for about 25%, and cropland for approximately 12%, making up about 98% of the area. The dynamic degree of construction land generally showed an initial increase followed by a decrease, but it remained positive, indicating a continuous growth in construction land area. In 1995-2000 and 2000-2005, we had the highest dynamic degrees, indicating the fastest growth in construction land area. Grassland consistently had negative dynamic degrees, indicating a continuous decline in the grassland area. Due to the small area of unused land, its dynamic degree was relatively unstable (Fig. 3).

This section employs the land-use transition matrix method to calculate land-use transition data. At the same time, ArcGIS 10.7 software is used to create visual representations of land-use changes and coverage (Fig. 4). Forest land is predominantly found in the northwestern part of the Jinsha River Basin in Yunnan Province. In contrast, cropland and construction land are mainly concentrated in the eastern and southeastern regions of the study area. The rapid pace of urbanization has led to a significant increase in construction land area since 2000, and this trend continues. Between 1985 and 2020, the primary land-use change in the Jinsha River Basin involved the conversion of grassland to other land-use types, particularly in the northeastern part of the study area, where cropland was mainly converted to other land-uses. The small area of construction land converted to other land-use types and the low precision of the data used mean that this conversion is not well depicted in the figures. The primary reasons for the continuous decrease in grassland area and the increase in construction land are the acceleration of urbanization, the advancement of industrialization and agricultural modernization, the demand for infrastructure development, and population growth. Urbanization increases the demand for urban construction land, industrialization and agricultural modernization convert grasslands into industrial zones and farmland, infrastructure development requires significant land, and population growth increases the need for housing and commercial land, converting extensive grasslands into construction land. This trend leads to environmental degradation and a reduction in biodiversity, challenging ecological balance.

Time-Series Variations in the Landscape Pattern Indices

Based on calculations using Fragstats 4.2 software at both class and landscape levels, we obtained the patch area (CA) and patch number (NP) for various landscape types in the Jinsha River Basin of Yunnan Province from 1985 to 2020. Subsequently, we derived and analyzed landscape pattern indices such as fragmentation, isolation, and disturbance using specific formulas (Fig. 5). The results indicate that from 1985 to 2020, the number of forest patches decreased, while the number of patches for cropland, grassland, water bodies, construction land, and unused land increased to varying extents. The most notable increases in cropland, grassland, and water bodies occurred between 1995 and 2000. The continual increase in patches across most landscapes is attributed to the conversion between different land-use types, leading to changes in landscape patterns. This conversion fragmented continuous natural landscapes into smaller patches, transforming the spatial distribution from contiguous areas to scattered patches, thereby increasing the complexity of landscape distribution. From 1985 to 2020, the landscape fragmentation index in the Jinsha River Basin, Yunnan Province, remained below 0.1, indicating a generally low level of fragmentation. However, cropland, water bodies, construction land, and unused land had higher fragmentation indices, reflecting lower stability and more significant disturbance from human activities. The isolation indices for grassland and water bodies increased yearly, while the construction land index gradually decreased. The fractal dimensions of all landscapes exhibited an upward trend, indicating that human activities and natural processes have made the landscape structure more complex and diverse. Urbanization and infrastructure development have diversified land-use types, making boundary shapes more complex and irregular. Agricultural activities and resource exploitation have further fragmented the land into smaller, more irregular parcels.

Moreover, natural disasters and ecological conservation efforts have significantly contributed to the increasing diversity and complexity of the landscape. Throughout the study period, the disturbance and loss indices for cropland, forest land, and construction land showed slight variation, trending towards a stable equilibrium. In contrast, the indices for grassland and water bodies experienced a slight increase. The landscape pattern indices for unused land exhibited significant fluctuations, mainly because unused land occupies a tiny fraction of the total study area, rendering it highly sensitive to the impacts of land-use type conversions.

Spatiotemporal Changes in Ecological Risk of Landscape Patterns

By computing the ecological risk values for each risk zone in the Jinsha River Basin of Yunnan Province from 1985 to 2020 and assigning these values to the center points of each risk zone, we then applied Kriging interpolation and visualization to these center point data. Drawing on relevant research [42-45], we employed the natural breaks classification method to categorize the landscape ecological risk results into five levels: low ecological risk zone ($ERI < 0.1400$), moderately low ecological risk zone ($0.1400 < ERI < 0.1606$), medium ecological risk zone ($0.1606 < ERI < 0.1730$), moderately high ecological risk zone ($0.1730 < ERI < 0.1844$), and high ecological risk zone ($ERI > 0.1844$). The ecological risk classifications for other years were aligned with the 1985 classification intervals to facilitate subsequent comparisons across different years.

From 1985 to 2020, the Jinsha River Basin in Yunnan Province was predominantly characterized by medium, moderately high, and high ecological risks, accounting for over 80% of the area (Fig. 6). Medium and moderately high ecological risks were the most prevalent, comprising approximately 30% of the study area. Low ecological risk was the least common, making up less than 0.3% of the area. The proportion of high ecological risk peaked in 2000, reaching 25.68% of the study area, a roughly 5% increase from 1995. This indicates that urbanization accelerated in the Jinsha River Basin during 2000, with significant increases in large-scale infrastructure construction, mineral resource exploitation, and agricultural expansion. These human activities led to severe fragmentation of natural landscapes and ecosystem degradation. Additionally, excessive development and improper land-use exacerbated soil erosion and biodiversity loss, placing immense pressure on the ecological environment. After 2000, the proportion of high ecological risk began to decline slowly but saw a slight increase by 2020. The proportion of moderately low ecological risk consistently decreased throughout the study period. In contrast, the proportions of low, medium, and moderately high

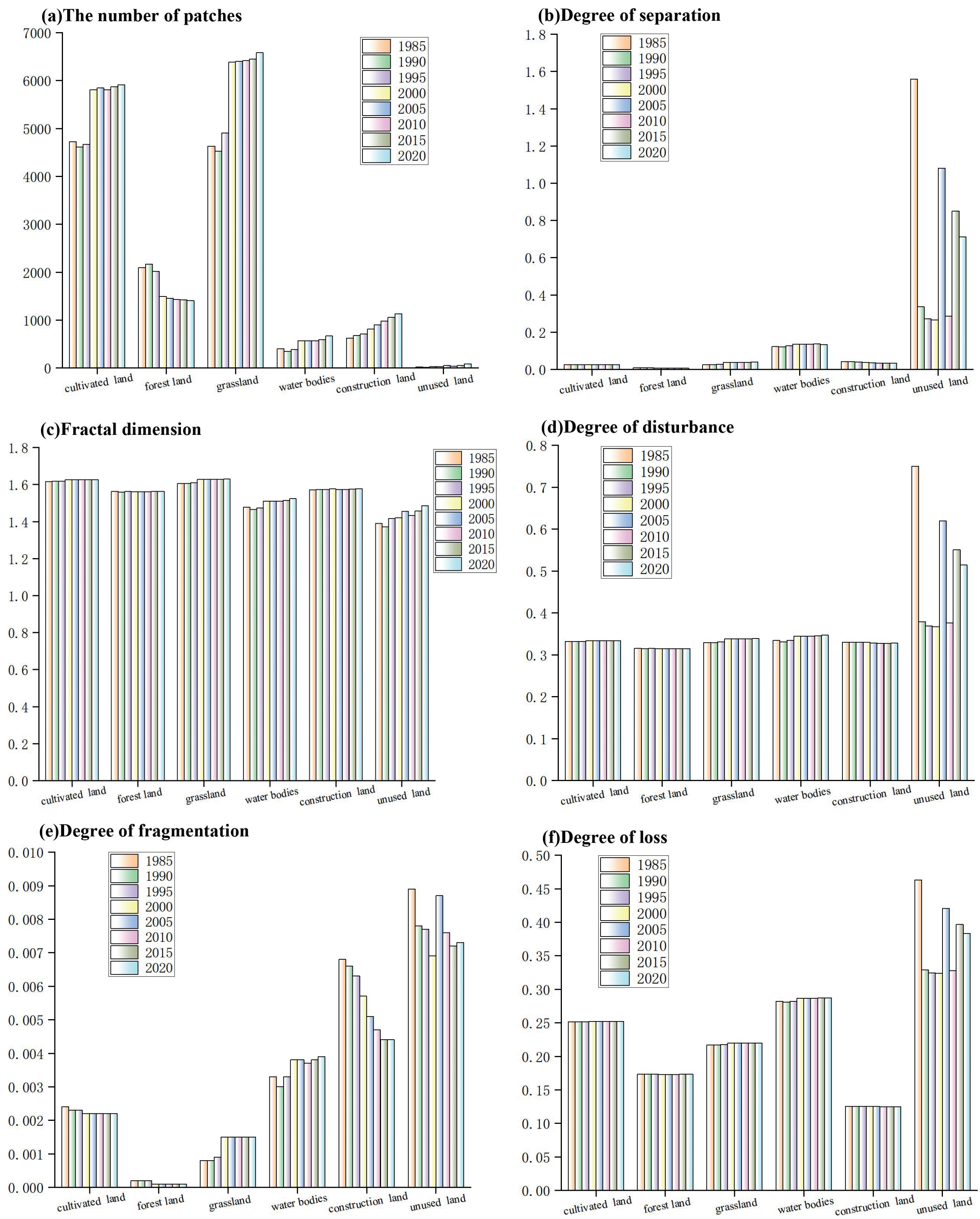

Fig. 5. Landscape pattern indices for various land types in the Jinsha River Basin, Yunnan Province, from 1985 to 2020.

ecological risks fluctuated, exhibiting patterns of increase, decrease, and subsequent increase.

Overall, the landscape ecological risk index in the Jinsha River Basin of Yunnan Province exhibits a pattern of higher risks in the central regions and lower risks in the peripheral areas. Spatially, high ecological risk zones are primarily located in Qujing City, Kunming City, northern Chuxiong Yi Autonomous Prefecture, eastern Dali Bai Autonomous Prefecture, and southwestern Zhaotong City. Most of these high-risk areas are concentrated in Kunming City and Qujing

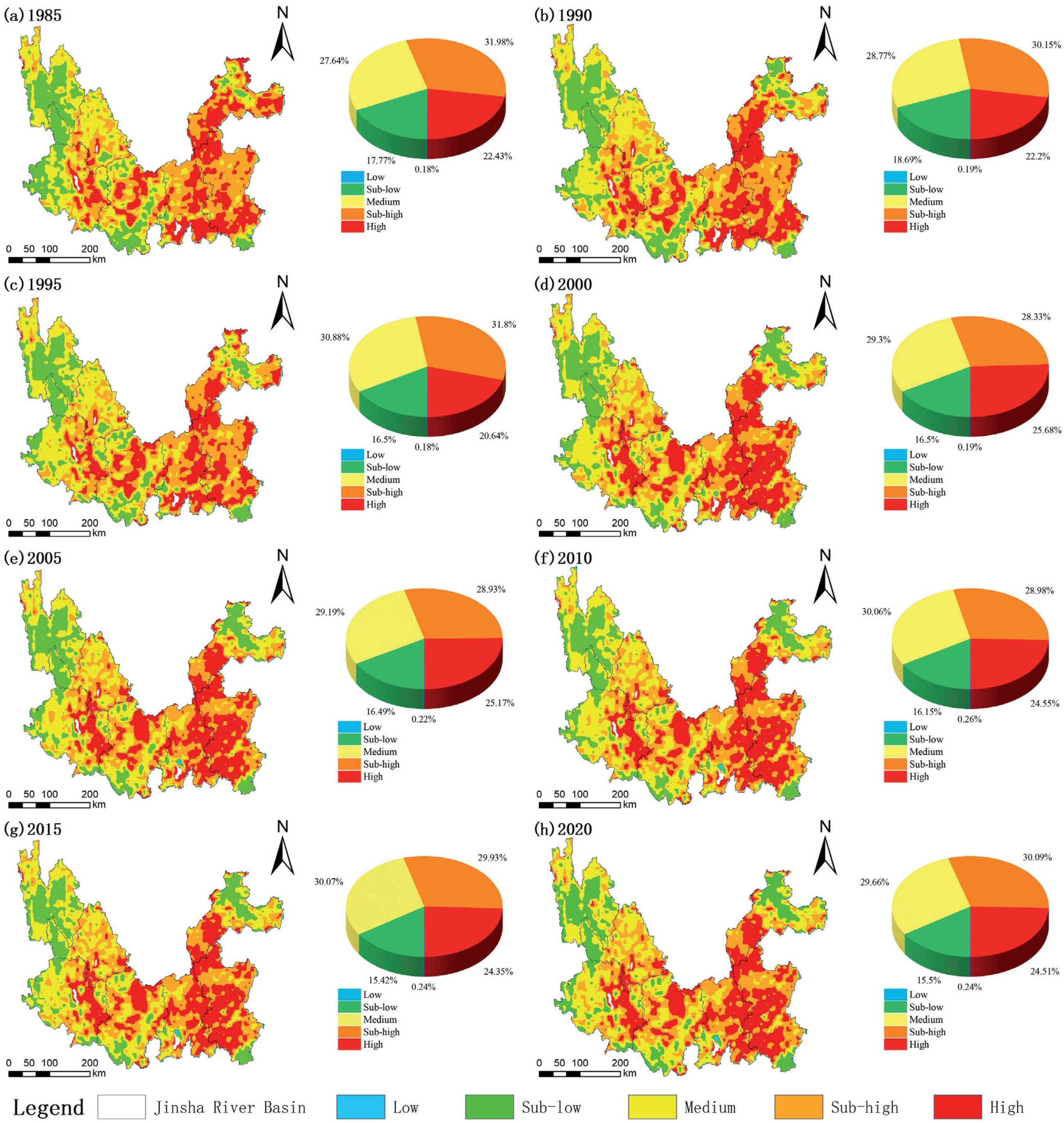

Fig. 6. Distribution and proportion of landscape ecological risks in the Jinsha River Basin of Yunnan Province from 1985 to 2020.

City, the economic and population centers of Yunnan Province. Rapid urbanization and industrialization in these regions have led to intense land development and resource utilization. As the provincial capital, Kunming City has a high population density, frequent infrastructure construction, and industrial activities, resulting in fragmented natural landscapes and degraded ecosystems. Qujing, a substantial industrial and agricultural base, faces additional ecological pressure from agricultural intensification, mineral resource extraction, and industrial pollution. Lower ecological risk areas are mainly found in Diqing Tibetan Autonomous Prefecture and northern Zhaotong City. These regions are relatively remote, with lower economic development, urbanization, and well-preserved natural environments. Diqing, located on a plateau with complex terrain and low population density, experiences minimal human disturbance, maintaining a relatively stable ecosystem. Similarly, northern Zhaotong, dominated by mountains and forests, sees limited agricultural and industrial development, with effective ecological protection measures and good soil and water conservation. These areas' rich natural resources and favorable ecological conditions reduce the likelihood of high ecological risks,

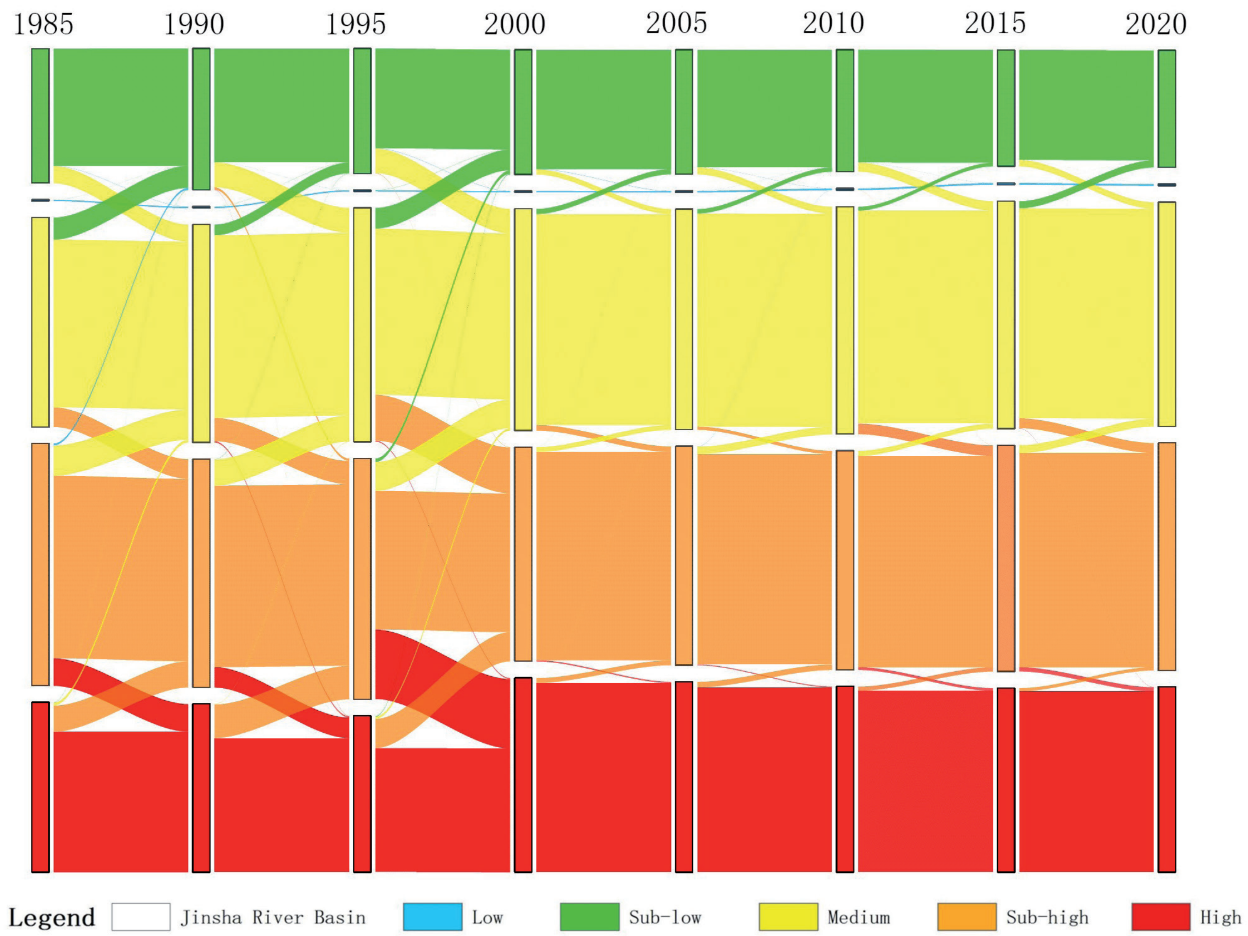

Fig. 7. Sankey diagram of landscape ecological risk transitions in the Jinsha River Basin, Yunnan Province from 1985 to 2020.

making them concentrated zones of lower ecological risk.

The transition matrix method calculates the landscape ecological risk transition matrix data. Subsequently, Origin 2022 software creates a Sankey diagram illustrating the transitions in landscape ecological risk (Fig. 7). ArcGIS 10.7 software produces a spatial distribution map of these transitions (Fig. 8). Throughout the study period, there was a continuous transition between different ecological risk levels, primarily among adjacent levels, resulting in changes in the area of each ecological risk level in the Jinsha River Basin of Yunnan Province across different years. From a temporal perspective, the extent of transitions between risk levels was substantial from 1985 to 2000 but decreased after 2000. Particularly from 1995 to 2020, there was a considerable shift from low to lower ecological risk, lower to moderate ecological risk, moderate to higher ecological risk, and higher to high ecological risk, with fewer reverse transitions. This led to an overall increase in landscape ecological risk during this period. From 1985 to 2020, areas with reduced risk levels were mainly found in Zhaotong City and near Dianchi Lake in Kunming City. However, with the rapid progress of urbanization and tourism development, construction land increasingly encroached on surrounding agricultural land, intensifying landscape disturbance. As a result, the landscape ecological risk levels in cities such as Kunming, Qujing, Lijiang, and Dali Bai Autonomous Prefecture increased.

Analysis of Spatial Autocorrelation in Landscape Ecological Risk

GeoDa software calculated the global Moran's I value for landscape ecological risk in each ecological subregion of the Jinsha River Basin, Yunnan Province (Fig. 9). Fig. 9 shows that the global Moran's I values for landscape ecological risk in the Jinsha River Basin from 1985 to 2020 were 0.242, 0.244, 0.219, 0.245, 0.241, 0.231, 0.228, and 0.226, respectively. These values, above 0.2, display an overall downward trend, suggesting a solid spatially positive correlation of landscape ecological risk in the study area. However, the spatial clustering is diminishing and is associated with changes in land-use and landscape patterns over the study period.

The LISA index was employed to analyze the local spatial autocorrelation of landscape ecological risk in the Jinsha River Basin, Yunnan Province, resulting in the LISA cluster map (Fig. 10). Given the large study area and the high proportion of non-significant clusters,

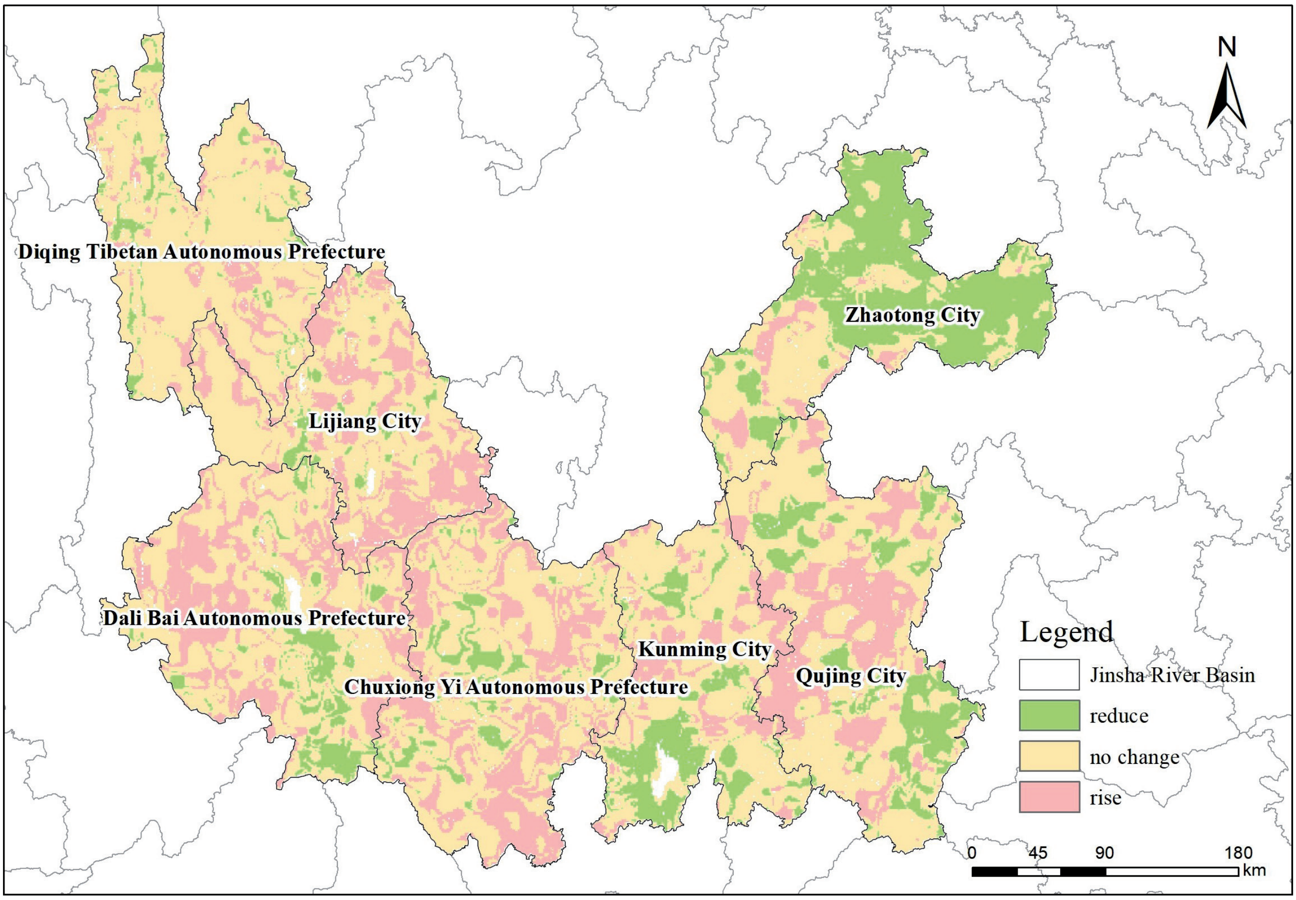

Fig. 8. Spatial distribution of landscape ecological risk transitions in the Jinsha River Basin, Yunnan Province from 1985 to 2020.

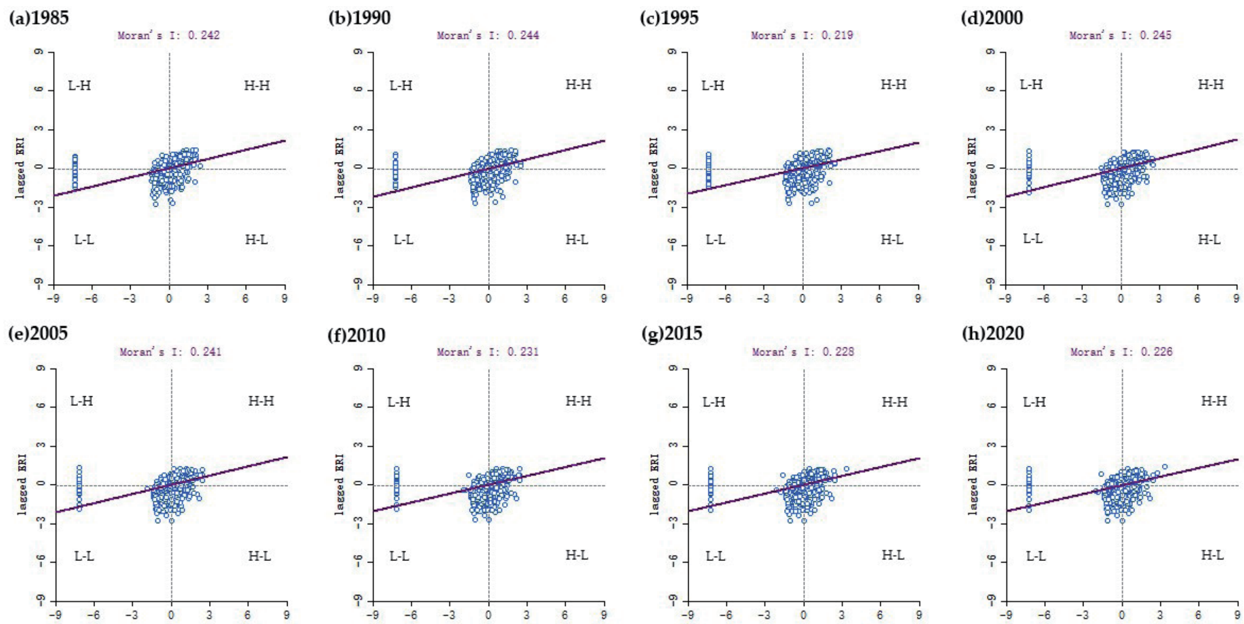

Fig. 9. Moran's scatter plots of landscape ecological risk in the Jinsha River Basin, Yunnan Province from 1985 to 2020.

the variations in other cluster types are relatively minor. Therefore, a table is used to more clearly show the changes in cluster types (Table 3). The spatial distribution in the Jinsha River Basin of Yunnan Province follows a “high in the center, low at the edges” pattern. Apart from non-significant risk units, the local spatial autocorrelation of landscape ecological risk is mainly characterized by “high-high” (H-H) and “low-

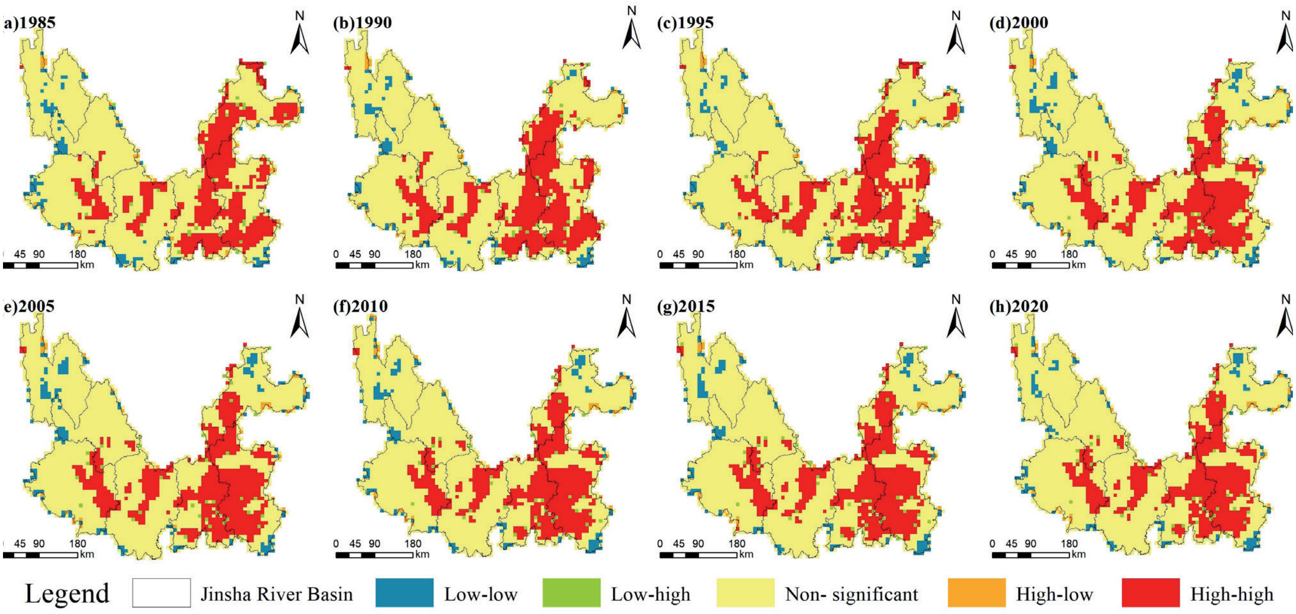

Fig. 10. Distribution map of local spatial autocorrelation of landscape ecological risk in the Jinsha River Basin, Yunnan Province from 1985 to 2020.

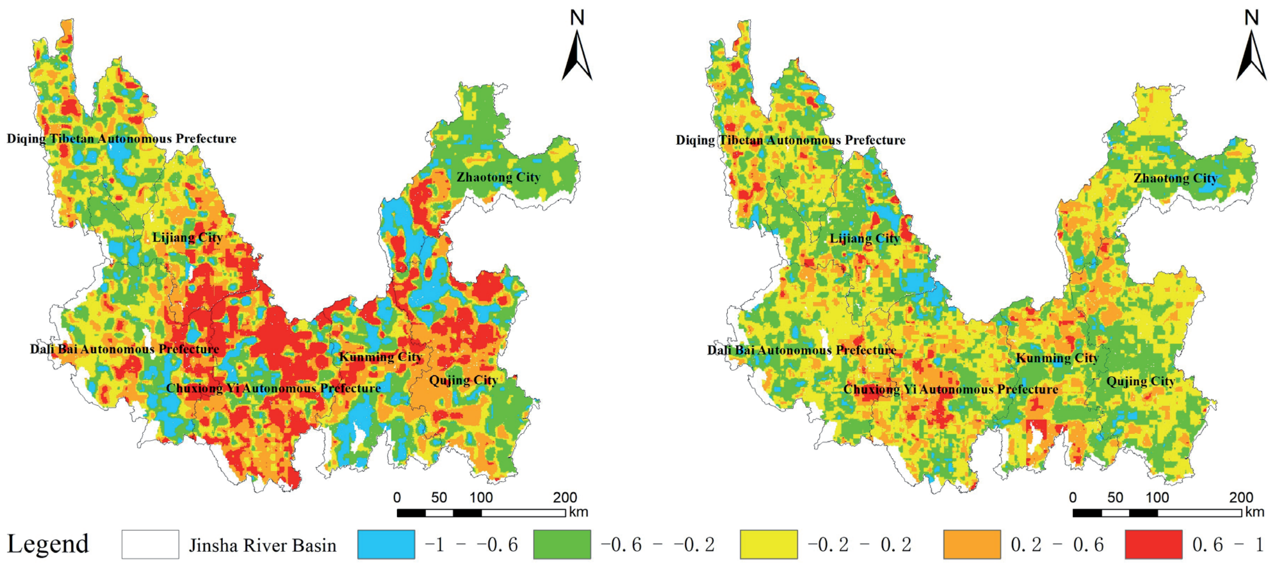

Fig. 11. Analysis of partial correlation between climatic factors and landscape ecological risk. (a) Partial correlation coefficient of landscape ecological risk with annual mean temperature, controlling for annual mean precipitation; (b) Partial correlation coefficient of landscape ecological risk with annual mean precipitation, controlling for annual mean temperature.

low" (L-L) clusters, with "low-high" (L-H) and "high-low" (H-L) spatial distributions being less prevalent. Generally speaking, the "low-high" (L-H) cluster areas are increasing, while the "high-high" (H-H) cluster areas are continuously decreasing. Analyzing the local spatial autocorrelation characteristics, the "low-low" (L-L) clusters are mainly located in the peripheral regions of the study area, such as Diqing Tibetan Autonomous Prefecture, the western part of Dali Bai Autonomous Prefecture, and the northern and eastern parts of Zhaotong City. These regions are relatively remote, with low levels of economic development, fewer human activities, low land-use intensity, and stable ecosystems, resulting in low ecological risk clustering. On the other hand, the "high-high" (H-H) clusters are primarily found in Kunming and Qujing cities. These areas exhibit higher levels of urbanization and industrialization, dense populations, high land-use intensity, and frequent human activities, leading to significant disturbances to the natural environment. This increases ecosystem vulnerability, exacerbates environmental pollution, and leads to overexploitation of resources, resulting in high landscape ecological risk clustering.

Table 3. Distribution of Cluster Types in the Jinsha River Basin, Yunnan Province from 1985 to 2020.

Year	Agglomeration Type				
	Non-significant	Low–low	Low–high	High–low	High–high
1985	2078	125	36	38	749
1990	2054	120	33	39	780
1995	2140	102	30	39	715
2000	2084	143	33	38	728
2005	2087	145	35	36	723
2010	2095	136	36	39	720
2015	2102	134	41	37	712
2020	2136	126	38	34	692

Analysis of Factors Influencing Landscape Ecological Risk

This study employs MATLAB software to perform a partial correlation analysis for the Jinsha River Basin in Yunnan Province (Fig. 11). This area is predominantly characterized by forest land and grasslands, with climatic factors exerting a significant influence. Changes in landscape patterns can also lead to variations in landscape ecological risk. This paper calculated the partial correlation between landscape ecological risk and climatic factors. The results show that in most regions, the annual mean temperature is positively correlated with ecological risk, while the annual mean precipitation is mainly negatively correlated. This is primarily because rising temperatures can increase evaporation rates, cause water shortages, and elevate drought frequency, thereby increasing ecosystem vulnerability and risk. Additionally, higher temperatures may boost the proliferation and spread of harmful organisms, further threatening ecosystem stability. Conversely, the negative correlation between annual mean precipitation and ecological risk is primarily due to increased rainfall replenishing water resources, improving soil moisture, promoting vegetation growth, and aiding ecosystem recovery. This reduces ecological stress from drought and water shortages, lowering ecological risk.

When the influence of annual mean precipitation is controlled, the areas where the annual mean temperature is negatively correlated with ecological risk are mainly distributed along the edges of the Jinsha River Basin in Yunnan Province. In contrast, the areas with a positive correlation are concentrated in the central region of the basin. Conversely, when the influence of annual mean temperature is controlled, the regions where annual mean precipitation is negatively correlated with ecological risk are scattered, with the primary concentrations in Qujing City, Zhaotong City, and Lijiang City. The areas with a positive correlation are predominantly located in Kunming City and Chuxiong Yi Autonomous Prefecture.

Discussion

Analysis of Land-Use Change

In the Jinsha River Basin of Yunnan Province, the grassland area has continuously decreased while construction land has steadily increased. The dynamics of construction land-use initially showed an increasing trend, followed by a decrease, with changes in various land-use types slowing down after 2000. With rapid economic development and continuous population growth, Yunnan Province has accelerated industrialization and urbanization. As a crucial economic belt of Yunnan Province, the Jinsha River Basin supports numerous infrastructure projects, including hydropower stations, highways, and railways. The growing population and accelerated urbanization have increased the demand for housing, transportation, and public facilities, directly driving urban expansion and the increase in construction land, reducing grassland areas. As ecological problems intensify, the government and society have placed greater emphasis on ecological protection, implementing a series of ecological restoration and conservation projects, such as the comprehensive Grain for Green Project initiated in 2002 [46]. This significant measure in China aims to make rational use of land resources and improve the ecological environment [47], thereby altering the land-use structure to some extent and alleviating the ecological pressure caused by land-use changes.

Analysis of Changes in Landscape Ecological Risk

The landscape ecological risk is intimately associated with landscape pattern indices such as patch number, fragmentation, and separation [48]. The study shows that the landscape pattern has limited resistance to external disturbances. From 1985 to 2020, most landscapes in the Jinsha River Basin of Yunnan Province experienced a continuous increase in patches. This rise results from the interconversion of different land-use types, which modified the landscape pattern, fragmenting previously continuous natural landscapes into smaller patches. Spatially, these patches shifted from a sheet-like distribution to a scattered, patchy distribution, making the landscape pattern more complex. In terms of time, the overall ecological risk level in the study area demonstrates a trend of initially decreasing and then increasing. The proportion of high and very high ecological risk levels grew most significantly from 1995 to 2000. Between 1995 and 2020, many ecological risk levels were upgraded to higher categories. The increase in ecological risk levels can be attributed to several factors: (1) Large-scale infrastructure projects, including hydropower stations and transportation networks, have disrupted natural ecosystems. (2) The advancement of agriculture and industry has further intensified ecological risk. Agricultural expansion has led to overexploitation of land and excessive use of pesticides and fertilizers, resulting in soil and water contamination. The rise in industrial activities has increased wastewater and air emissions, worsening environmental pollution. Notably, extracting specific mineral resources has caused irreversible damage to local ecosystems. (3) Climate change has also significantly impacted ecological risk in the Jinsha River Basin of Yunnan Province. Global warming has resulted in more frequent extreme weather events, such as floods and droughts, which threaten the ecological environment and further increase ecological risk levels. The frequent disturbances from human activities have intensified the pressure on fragile ecosystems. The “high-high” (H-H) clusters are predominantly found in economically developed areas like Kunming City and Qujing City, which are highly urbanized and industrialized, densely populated, and characterized by high land-use intensity, leading to considerable disturbances to the natural environment. In contrast, the “low-low” (L-L) clusters are mainly located in the more remote regions of Diqing Tibetan Autonomous Prefecture, the western part of Dali Bai Autonomous Prefecture, and the northern and eastern parts of Zhaotong. These areas are relatively isolated, primarily consisting of rich biodiversity forests, and have a more stable ecosystem [49]. With high vegetation coverage, lower economic development, and fewer human activities, these regions exhibit low land-use intensity and a stable ecosystem, experiencing minimal external disturbance [50]. High vegetation coverage can influence regional landscape patterns and functions [51]; areas with dense vegetation can improve resilience to disturbances and support sustainable development. Thus, there is a strong connection between landscape ecological risk and land-use types.

Analysis of Factors Influencing Landscape Ecological Risk

The land-use types in the Jinsha River Basin of Yunnan Province are primarily cropland and grassland, which have a relatively weak capacity to withstand external risks and are particularly susceptible to environmental factors, especially climate [52]. Therefore, changes in annual average temperature and precipitation are significant factors affecting the ecological environment of the Jinsha River Basin. Partial correlation results indicate that, when controlling for annual precipitation, there is a positive correlation between annual average temperature and ecological risk. Conversely, there is a negative correlation between annual precipitation and ecological risk when controlling for annual average temperature. Relevant studies indicate that climate change is closely related to land-use changes, highlighting that climate change primarily affects vegetation growth, influencing ecological risk [53]. High temperatures accelerate evaporation and transpiration, reducing soil moisture and inhibiting vegetation growth, especially when precipitation remains constant. High temperatures may also increase the frequency and intensity of wildfires, damaging forest and grassland ecosystems, reducing biodiversity, and thereby increasing ecological risk. Additionally, under high-temperature conditions, the demand for water resources increases, but supply is insufficient, leading to water scarcity issues that further exacerbate ecological risk. Precipitation is crucial in maintaining ecosystem health; adequate rainfall increases soil moisture, promotes vegetation growth, and enhances ecosystem stability and resilience. Within specific temperature and precipitation ranges, annual average temperature is generally positively correlated with landscape ecological risk, while annual precipitation is negatively correlated. In other words, the more precipitation and the lower the temperature, the lower the ecological risk. However, under extreme climate conditions, ecological risk will still intensify [54].

Guidelines for the Prevention and Control of Landscape Ecological Risks

Against the backdrop of rising overall landscape ecological risk in the Jinsha River Basin of Yunnan Province, the following recommendations are proposed for the study area: (1) Strengthen ecological protection and restoration efforts, with increased emphasis on protecting the ecosystems of the Jinsha River Basin, particularly critical ecosystems such as forests, wetlands, and grasslands. Forests and grasslands are crucial for maintaining ecological stability. Implement ecological restoration projects to enhance the self-repairing capacity of ecosystems. (2) Plan and manage land-use rationally to avoid overdevelopment and unsustainable land-use practices. Strengthen ecological and environmental assessments of activities such as mineral resource exploitation and infrastructure construction to ensure these activities occur within the ecological carrying capacity. (3) Promote ecological agriculture and green development by encouraging and supporting the growth of ecological agriculture, reducing the use of chemical fertilizers and pesticides, and promoting organic farming and ecological planting techniques. By developing green industries such as eco-tourism and renewable energy, we can balance economic development and ecological protection harmoniously.

Limitations and Future Prospects

This study evaluates the landscape ecological risk and spatial pattern evolution in the Jinsha River Basin of Yunnan Province from 1985 to 2020, based on land-use/cover data. Understanding the temporal and spatial variations in landscape ecological risk and its spatial differentiation is crucial for formulating scientifically sound land-use planning in the region, thereby reducing ecological risk and achieving sustainable development. However, this research has some limitations. Firstly, with the diversification of current assessment methods, it is essential for models to comprehensively consider the functions and structures of the watershed's ecological environment and external environmental influences. Secondly, this paper only analyzes the landscape structure of the study area without assessing aspects such as ecosystem service functions. Therefore, future research should integrate an evaluation of the watershed's ecological functions, structures, and external influences, along with an assessment of ecosystem service functions in the study area.

Conclusions

Focusing on the Jinsha River Basin in Yunnan Province, this study utilizes land-use raster data from 1985 to 2020 to build a landscape ecological risk assessment model for the watershed. The comprehensive analysis addresses land-use changes and transitions, spatiotemporal dynamics of landscape pattern ecological risk, spatial autocorrelation of landscape ecological risk, and influencing factors. The study arrives at the following conclusions:

(1) From the perspective of land-use dynamics, the landscape types in the Jinsha River Basin of Yunnan Province are primarily composed of arable land, forest land, and grassland, which together account for approximately 98% of the total area of the study region. Notably, the built-up land area is steadily increasing, while the grassland area is declining. (2) The number of forest patches in the study area has decreased. In contrast, the number of patches for arable land, grassland, water bodies, built-up areas, and unused land has increased to varying degrees. The landscape fragmentation index is consistently below 0.1, indicating a generally low level of landscape fragmentation. (3) The landscape ecological risk assessment results reveal that the region is predominantly characterized by moderate, relatively high, and high ecological risks, which account for over 80% of the total area. Among these, moderate and relatively high ecological risks are the most significant. Spatially, high ecological risk areas are primarily located in Qujing City, Kunming City, northern Chuxiong Yi Autonomous Prefecture, eastern Dali Bai Autonomous Prefecture, and southwestern Zhaotong City, with a substantial concentration of high ecological risk areas found in Kunming and Qujing. (4) The global Moran's I value for landscape ecological risk is consistently above 0.2 and shows a downward trend, indicating a solid spatial positive correlation in the ecological risk of the study area, although spatial clustering is diminishing. The distribution of landscape ecological risk follows a pattern of "high in the middle, low at the edges." Aside from units without significant risk, the spatial distribution of landscape ecological risk in the area is primarily characterized by "high-high" (H-H) and "low-low" (L-L) clusters, with "low-high" (L-H) and "high-low" (H-L) distributions being relatively minor. (5) Controlling for the influence of average annual precipitation, the average annual temperature in the region shows a positive correlation with the level of ecological risk, while controlling for average annual temperature, average annual precipitation exhibits a negative correlation with ecological risk levels.

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Conflict of Interest

The authors declare no conflict of interest.

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