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Landscape Ecological Risk Assessment and Spatial Pattern Evolution Analysis of the Central Yunnan Urban Agglomeration from 1995 to 2020 Based on Land Use/Cover Change

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Abstract: The central Yunnan urban agglomeration represents a typical urban cluster in the southwestern region of China. The swift urbanization and land use changes in this region pose a severe threat to the ecosystem. A thorough assessment of the landscape ecological risk in the central Yunnan urban agglomeration holds paramount importance for devising effective risk management strategies and sustainable, high-quality development plans. This study utilizes long-term land-use raster data for six time periods (1995, 2000, 2005, 2010, 2015, and 2020) in the Central Yunnan urban agglomeration. Using GIS technology, a landscape risk index model is constructed, and a comprehensive assessment of landscape ecological risks in the Central Yunnan urban agglomeration is conducted using the 5 km $\times$ 5 km grid analysis method and Kriging interpolation. The results indicate that, between 1995 and 2020, the Central Yunnan urban agglomeration was dominated by forest land, grassland, and cultivated land as the primary land-use types. Forest land covered over 48% of the total area, while grassland and cultivated land accounted for more than 26% and 18%, respectively. Notably, construction land underwent a significant increase, mainly due to conversions from cultivated land, forest land, and grassland. Over a span of 25 years, the study area has experienced a continual rise in landscape ecological risk. The landscape ecological risk was mainly characterized by medium, higher, and high ecological risk. Grassland predominated in areas with medium levels of ecological risk, while cultivated land and construction land were predominant in regions with higher and high levels of ecological risk. Spatially, regions with lower ecological risk were primarily distributed in the Chuxiong Yi Autonomous Prefecture, whereas areas with higher and high levels of ecological risk were concentrated in Qujing City and Kunming City. The spatial aggregation patterns of landscape ecological risk in the Central Yunnan urban agglomeration featured "high–high" (H–H) and "low–low" (L–L) clusters, both displaying an initial increase followed by a decrease. The primary factors contributing to the rise in the landscape ecological risk index were identified as urban expansion, population growth, ecological fragmentation, and vegetation destruction. The study's outcomes can offer valuable insights for optimizing land resources and promoting sustainable development in the Central Yunnan urban agglomeration.

Keywords: central Yunnan urban agglomeration; land use/cover change; gridding; landscape index; landscape ecological risk assessment; spatial autocorrelation

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1. Introduction

With the rapid growth of the global population and the accelerated urbanization processes in major urban agglomerations, there has been a significant intensification of changes in land use and land cover. Research indicates that land-use changes are increasingly prominent in terms of their impact on ecosystems, directly influencing regional landscape patterns and ecological sustainability [1–3]. In the last 25 years, China has undergone rapid urbanization processes, characterized by increasingly intense land use, dramatic alterations in land use/cover, and an intensified ecological risk stemming from land use [4]. The rapid expansion and overdevelopment of urban clusters can easily result in a fragmented landscape pattern of land use, diminishing the natural protective capacity of land use and disrupting the existing ecological structure. Unreasonable changes in land use amplify potential risks to ecosystems, biodiversity, and the ecological environment. The study found that land use/cover change plays a decisive role in regional ecological risks [5]. As the fundamental unit of human activities [6], rooted in landscape patterns, the ecological risk assessment of land use/cover change is a crucial approach for evaluating and analyzing the potential risks and impacts of land use on ecosystems. Commencing from the spatial dimension of the landscape, it identifies ecological risks within the land use/cover change landscape pattern of swiftly expanding urban clusters. This transformation of landscape spatial structure into spatialized ecological risk variables facilitates the comprehension of the spatiotemporal changes and spatial heterogeneity of ecological risks [7]. Detecting ecological risks in a timely manner and implementing responsive measures play a crucial role in avoiding or mitigating potential ecological disasters and environmental damage. The continual optimization of the land-use pattern and structure is pursued to maximize the protection and restoration of ecosystems.

The assessment of ecological risk in the landscape patterns of land use/cover change typically employs quantitative analysis methods. The model quantifies the impact of land use on the ecological environment through selected landscape pattern indicators, addressing the limitations of traditional qualitative analysis. Consequently, the assessment results are more objective and accurate. In the context of landscape ecological risk assessments related to changes in land use/cover, extensive research has been conducted by scholars globally. Ayre et al. [8] employed a Bayesian network model to assess ecological risks in the forest landscape of Oregon, USA. Paukert et al. [9] developed an ecological risk index at the landscape scale, considering both land-use changes and landscape structures. Du et al. [10] analyzed the spatiotemporal evolution of land cover changes in the Yellow River Basin from 2015 to 2020 and conducted an assessment of landscape ecological risk. Jin et al. [11] utilized a method based on changes in land use/cover to assess urban ecological risks on the Qinghai–Tibet Plateau. Li et al. [12] analyzed the spatiotemporal evolution of landscape ecological risk in the Zhoushan Islands region from 2000 to 2020. The existing studies have predominantly focused on the post-2000 timeframe, revealing a scarcity of research before the year 2000. From the perspective of research methods, the ecological risk assessment of landscape patterns resulting from land use/cover change requires high-precision land-use data, and obtaining and processing it involves certain technical difficulties and costs. The selection of parameters and uncertainties in the evaluation model can impact the assessment results, necessitating a reasonable choice of research scale to obtain reliable assessment outcomes. In terms of the research scope, the primary focus has been on key regions such as watersheds [13–16], developed cities [17–19], and coastal zones [20–22]. However, there is a notable gap in research, particularly concerning the highland mountainous urban clusters characterized by ecological fragility and sensitivity. This gap is especially pronounced in the context of the southwestern highland mountainous urban clusters in China. Against this backdrop, it is imperative to conduct a landscape pattern ecological risk assessment and analyze the spatial pattern evolution of changes in land use/cover in highland mountainous urban clusters. Understanding its spatiotemporal characteristics promotes the balanced development of ecology, economy, and society, ensuring the efficiency maximization of land resource utilization and sustainable ecological development. This study contributes to the formulation of scientifically reasoned land planning decisions and environmental management measures.

Building on this foundation, the present study has its basis in land use/cover changes. The Central Yunnan urban agglomeration is selected as the research area due to its prominent and drastic changes in land use/cover, its ecological fragility, and the heightened ecological risks it has faced over the past 25 years. Utilizing land-use data from 1995 to 2020, this study constructs a landscape ecological risk index. Employing GIS spatial analysis, statistical methods, and grid-scale analysis, the research investigates the spatial differentiation characteristics of changes in land use/cover and landscape ecological risks in the Central Yunnan urban agglomeration. This research aims to address the gaps in existing studies related to the long-term assessment of landscape patterns and ecological risks related to changes in land use/cover in this region. The investigation delves into the temporal evolution of landscape ecological risks in the Central Yunnan urban agglomeration, providing a scientific basis for formulating effective risk management strategies and sustainable development plans for the region.

2. Data and Methods

2.1. Overview of the Study Area

The Central Yunnan urban agglomeration is between 100°43′ to 104°49′ E longitude and 24°58′ to 25°09′ N latitude (Figure 1). This region represents the central core of Yunnan Province's development, covering approximately 29% of the total provincial land area. As of the end of 2020, the population in this area accounted for approximately 44.02% of the total provincial population. The urban agglomeration in Central Yunnan has a high-altitude and low-latitude plateau monsoon climate. It is dominated by the lake basin karst plateau landform. It is a typical mountainous urban agglomeration in the high plateau region, with relatively flat terrain; two-thirds of the province's plains are concentrated here, and it boasts Yunnan's most advantageous land resources. However, certain areas exhibit exceptionally fragile ecological environments.

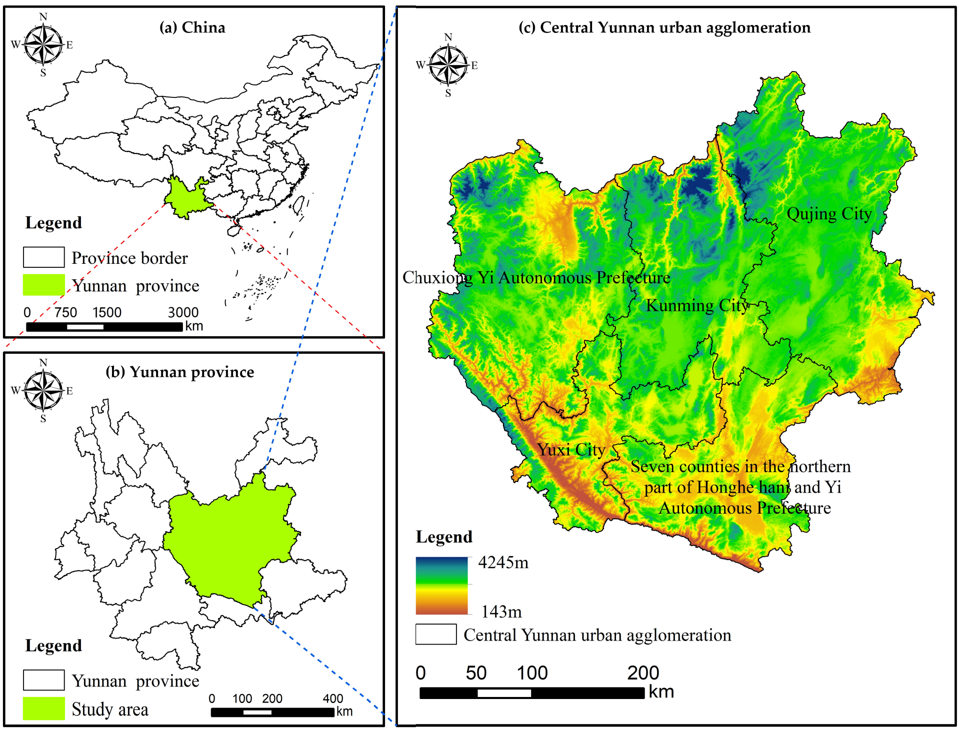

Figure 1. (**a**) The study area's provincial location within China, map approval number: GS(2019)1822; (**b**) the position of the study area within Yunnan Province; (**c**) distribution of elevation in the research area.

The years between 1995 and 2020 marked a period of swift economic growth, coupled with a significant rise in the population of the Central Yunnan Urban Agglomeration. However, this phase also saw the emergence of significant conflicts between land resources, population, and sustainable economic development, leading to a continuous weakening of the region's resources and environmental carrying capacity. Therefore, undertaking a comprehensive, long-term assessment of the landscape ecological risk associated with land use in the Central Yunnan urban agglomeration is of paramount importance for fostering high-quality and sustainable development in this region.

2.2. Data Sources

The land-use data is acquired from the Chinese Academy of Sciences Resource and Environment Data Center (https://www.resdc.cn/ (accessed on 17 April 2023)) [23] and features a spatial resolution of 1 km. The interpretation of land-use data for each period between 1995 and 2010 was conducted using Landsat-TM/ETM remote sensing imagery. In contrast, for the years 2015 and 2020, Landsat 8 remote sensing imagery was utilized. The interpretation of land-use data involved a manual visual interpretation process based on the spectral characteristics of remote sensing images from the corresponding year, combined with field measurements and considerations of geometric shape, color features, textural characteristics, and spatial distribution. To ensure the quality and consistency of land-use interpretation across different periods, a unified quality control and verification process was applied to the dataset. The land was categorized into cultivated land, forest land, grassland, water area, construction land, and unused land based on the attributes of land resources and utilization. The final comprehensive accuracy of the land-use evaluation exceeded 93% [24], meeting the precision requirements for the study area. The projection of land-use data employs the Albers equal-area conic projection with standard parallels, ensuring spatial accuracy. The GIS software ArcGIS 10.7 was employed to crop the multi-temporal land use/cover remote sensing monitoring data for the study period, utilizing the foundational geographic data of the Central Yunnan urban agglomeration.

2.3. Research Methods

This study primarily employs indicators such as land-use dynamics and land-use transition matrices to analyze the spatiotemporal patterns of land use in the Central Yunnan urban agglomeration from 1995 to 2020. Furthermore, it constructs a comprehensive assessment model for landscape ecological risk using GIS grid analysis. Spatial autocorrelation methods are utilized to analyze the clustering characteristics and trends in landscape ecological risk within the study area. Figure 2 displays the schematic representation of the research framework in this study.

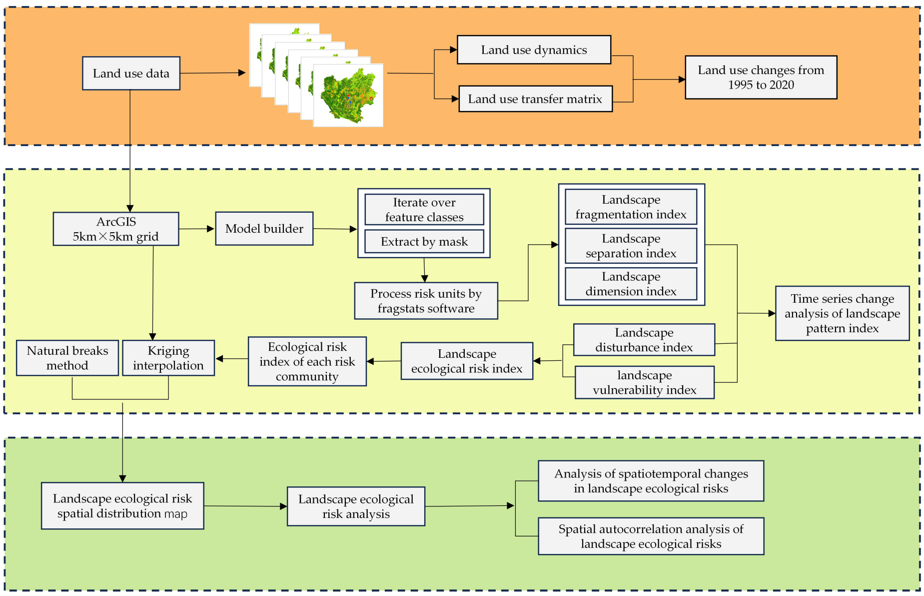

Figure 2. Framework diagram of the study.

2.3.1. Degree of Land-Use Dynamics

The term "single land-use dynamic degree" indicates the changes or transitions that occur in a specific land-use type over a certain period, serving as a crucial indicator for measuring the speed and extent of land-use change [25]:

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

In the study period, K represents the dynamism of a specific land-use type. U_a and U_b signify the land-use areas during the study's inception and culmination, with T specifying the study's timeframe.

2.3.2. Land-Use Transfer Matrix

A fundamental tool in the realms of land-use planning, land resource management, and ecosystem research, the land-use transition matrix is instrumental in portraying the shifts between various land-use categories in a specified area across different temporal phases. The mathematical expression is as follows [26]:

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

The symbol $\mathrm{S_{ij}}$ in the equation signifies the alteration in the area of a given land-use category from the research's inception to its conclusion, with n representing the total number of land-use categories.

2.3.3. Evaluation Unit Division

This study adopts a landscape ecology perspective to establish a regional ecological risk assessment model for the Central Yunnan urban agglomeration. Using Fragstats 4.2 software, three initial parameters were calculated based on the land-use data for six periods spanning from 1995 to 2020: the total area of each landscape (CA), the number of landscape patches (NP), and the landscape perimeter (PERM). Landscape ecological methods were then employed to select risk assessment indicators, which included landscape metrics such as landscape fragmentation, isolation, dimension, disturbance, fragility, and loss indices. These indices were used to formulate the Landscape Ecological Risk Index (ERI), thereby depicting the spatial differentiation and pattern alterations in ecological risk within the Central Yunnan urban agglomeration. Using ArcGIS 10.7 software, the Central Yunnan urban agglomeration was partitioned into risk zones. Cell size selection followed the principle of 2 to 5 times the average patch size [27,28], resulting in a final sampling area size of 5 km × 5 km. The entire study area was divided into 4708 risk zones.

2.3.4. Landscape Ecological Risk Index

The ecological risk assessment model, established using the initial parameters, was used to calculate values for each risk zone, resulting in a risk index as the parameter value for each cell. Subsequent to this step, the ecological risk spatial patterns for the entire study region were visualized employing the Kriging interpolation technique, and the computation was executed using the subsequent formula [29]:

$$ERI_i = \sum_{i=1}^{n} \frac{A_{ki}}{A_k} \times R_i \quad (3)$$

In this context, n signifies the number of landscape categories, A_{ki} denotes the area of landscape category i within the k-th risk zone, A_k represents the area of the k-th risk zone, and R_i indicates the degree of landscape loss. The detailed formulas and explanations are presented in Table 1.

Table 1. Formula and significance of landscape pattern indices computation.

Landscape Pattern Index	Calculation Formula	Parameter Meaning
Landscape fragmentation C_i	$C_i = \frac{n_i}{A_i}$	Within the expression, A_i denotes the area of landscape category i, n_i represents the number of patches. C_i indicates the extent of landscape fragmentation, with larger values suggesting diminished landscape security [30].
Landscape separation N_i	$N_i = \frac{A}{2A_i}\sqrt{\frac{n_i}{A_i}}$	The formula includes A, which represents the total landscape area. A higher numerical value of N_i signifies a more widely distributed spatial arrangement of the landscape [31].
Landscape dimensions F_i	$F_i = 2\ln(p_i/4)/\ln A_i$	P_i in the formula corresponds to the perimeter of landscape category i. F_i denotes the fractal dimension of the spatial distribution of diverse individual elements within a specific landscape type [32].
Landscape interference U_i	$U_i = \mathrm{a}C_i + \mathrm{b}N_i + \mathrm{c}F_i$	In the expression, a, b, c are the weights of the corresponding landscape indexes, and a + b + c = 1, where a = 0.5, b = 0.3, c = 0.2 [33]. U_i denotes the degree of disturbance experienced by the ecosystem, with higher values indicating increased ecological risk.
Landscape vulnerability E_i	The six types of landscape types are assigned values through the expert scoring method and finally normalized to obtain the landscape vulnerability index [34,35] (Table 2).	As the value of E_i increases, the ability to resist external disturbances weakens, leading to a heightened ecological risk.
Landscape loss R_i	$R_i = \sqrt{U_i \times E_i}$	R_i is the combination of a certain landscape's disturbance degree and vulnerability index [36].

Table 2. Table of the landscape vulnerability assessment.

Type	Landscape Type	Landscape Vulnerability Index	Index Normalization
1	cultivated land	4	0.19
2	forest land	2	0.10
3	grassland	3	0.14
4	water area	5	0.24
5	construction land	1	0.05
6	unused land	6	0.29

2.3.5. Spatial Autocorrelation Analysis

This is a statistical technique employed to examine the spatial correlation of geographical phenomena. Grounded in the characteristics of geographical spatial data, it involves computing the spatial relationships between geographical units to investigate the presence of spatial correlations within geographical phenomena. The primary function of the global *Moran's I* index is to portray the spatial correlation magnitude of a particular attribute value across the entirety of the dataset. The *Moran's I* index was chosen to examine the global spatial correlation within the study area, with values ranging from −1 to 1. A positive *Moran's I* value signifies a positive correlation, and as the value increases, the correlation becomes more pronounced. Conversely, a negative *Moran's I* value indicates a negative correlation, and with an increasing numerical value, the correlation becomes more pronounced. A *Moran's I* value of 0 implies no correlation [37]. The local spatial autocorrelation *LISA* index, alternatively referred to as the local *Moran's I* index, provides an effective description of the local spatial clustering of extreme values of spatial variables. It manifests in four specific types: the L–L type (low–low clustering), the H–H type (high–high clustering), the H–L type (low values around high values), and the L–H type (high values around low values). The formulas for both the global *Moran's I* and *LISA* indices are presented below [38]:

$$Moran's\ I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} W_{ij}(x_i - \overline{x})(x_j - \overline{x})}{S^2\sum_{i=1}^{n}\sum_{j=1}^{m} W_{ij}} \tag{4}$$

$$LISA = \left(\frac{x_i - \overline{x}}{m}\right)\sum_{i=1}^{n} W_{ij}(x_i - \overline{x}) \quad (5)$$

where x_i and x_j represent the observed values of a certain attribute for the spatial units x and j, respectively, W_{ij} denotes the spatial weight, and $\overline{x}$ is the mean of the variable, while S^2 represents the variance.

3. Results

3.1. Analysis of Land-Use Changes

3.1.1. Characteristics of Land-Use Structural Change

From 1995 to 2020, the primary land-use categories within the Central Yunnan urban agglomeration were forest land, grassland, and cultivated land (Figure 3). Among them, forest land stands out as the predominant land use category, encompassing more than 48% of the total study area. Following closely is grassland, constituting over 26% of the total area. Cultivated land occupies more than 18% of the study area, while the combined area of other land classes is less than 5%. Over the past 25 years, cultivated land, forest land, and grassland areas within the Central Yunnan urban agglomeration have consistently decreased, while water areas and construction land have seen continuous expansion. Among these changes, forest land experienced the most significant reduction, declining by 21.9862 × 10^4 square hectares. Conversely, construction land exhibited the most pronounced increase, growing by 13.5046 × 10^4 square hectares. The land-use dynamism of construction land has remained consistently high, with the most rapid expansion occurring between 2015 and 2020. The predominant driver behind the relentless expansion of construction land is persistent socioeconomic growth, an escalating population, and the ever-increasing levels of urbanization in the Central Yunnan urban agglomeration. Conversely, the principal factors contributing to the decline in forest land and grassland stem from the utilization of ecological land due to socioeconomic development, subsequently leading to environmental degradation.

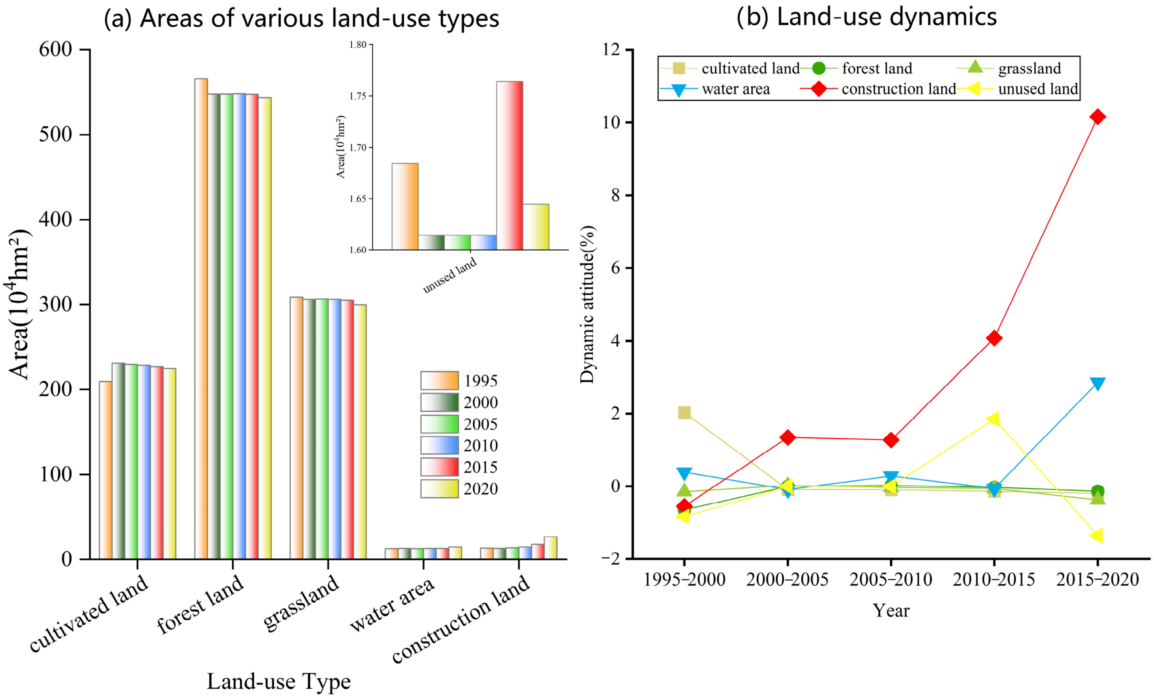

Figure 3. Areas of various land-use types and land-use dynamics in the Central Yunnan urban agglomeration from 1995 to 2020.

3.1.2. Characteristics of Transfers in Land-Use Types

Analyzing the land use type transition characteristics in the study area reveals that there was a significant transition between different land uses from 1995 to 2000. However, the transitions between land use from 2000 to 2005, 2005 to 2010, and 2010 to 2015 were not as pronounced (Figure 4). Between 2000 and 2015, no substantial land-use transitions were observed among the different land types. This can be attributed to the relatively modest economic development seen during this period. In contrast, the land-use transitions during other periods were primarily associated with cultivated land, forest land, and grassland, which collectively covered more than 95% of the total study area. These transitions displayed more evident changes. After 2015, as economic development accelerated more rapidly, transitions between various land types became more pronounced compared to the other periods. Apart from the transitions between the three aforementioned land types, other land categories also experienced changes. Furthermore, there was a noticeable shift in land types towards construction land. At the same time, various types of land were transferred more frequently to construction land, and unused land remained basically unchanged throughout the study period.

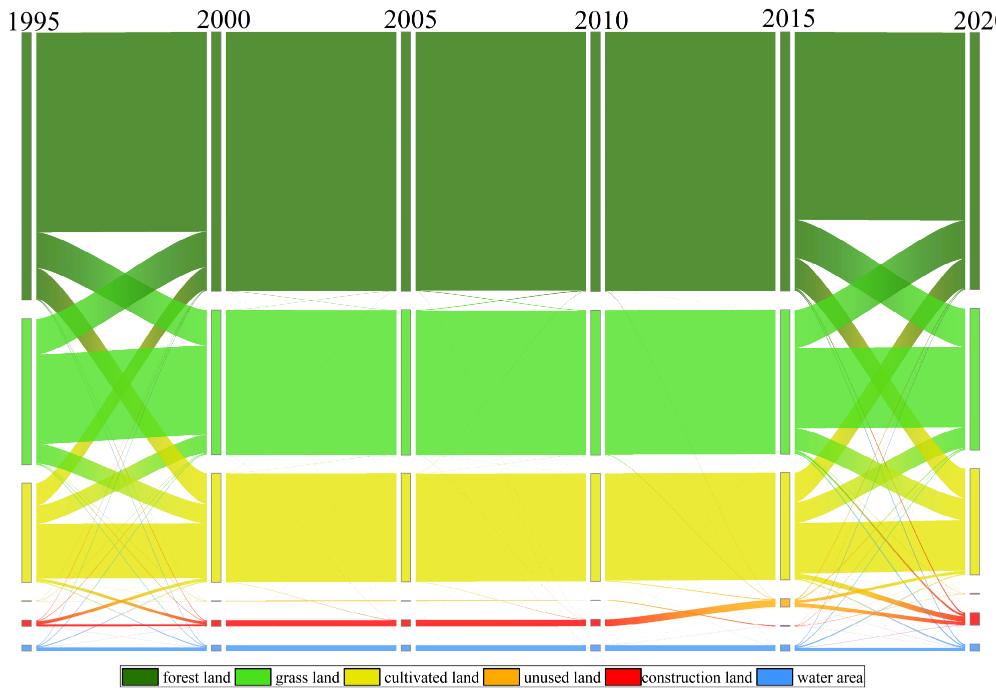

Figure 4. Sankey diagram of land-use transfers during various phases in the Central Yunnan urban agglomeration from 1995 to 2020.

3.2. Temporal Changes in the Landscape Pattern Index

Using Fragstats 4.2 software, landscape pattern indices for various land-cover types were computed at both the class and landscape levels. These indices were derived from landscape metrics such as the patch area (CA) and number of patches (NP). Analysis was conducted on landscape fragmentation, separation, and disturbance for the period of 1995 to 2020 in the Central Yunnan urban agglomeration (Figure 5). From a landscape perspective, it is evident that the landscape fragmentation of various land-cover types within the Central Yunnan urban agglomeration from 1995 to 2020 was consistently less than 0.01. The overall degree of landscape fragmentation remained relatively low. However, land-cover types such as cultivated land, water areas, construction land, and unused land exhibited higher landscape fragmentation indices, indicating that these land categories experienced significant human-induced disturbances. The number of patches for each land-cover type exhibited a yearly increasing trend. This is attributed to the interconversion among various land-use categories, resulting in alterations to the distribution pattern of patches. Previously continuous land areas are now fragmented into multiple discrete patches. Throughout the entire study period, the landscape separation of cultivated land, forest land, grassland, water areas, and unused land generally increased, while the landscape separation of construction land gradually decreased. The landscape dimensions and disturbance levels of cultivated land, forest land, and grassland did not fluctuate much during the study period and were in a stable state. The higher degree of interference in water areas, construction land, and unused land indicates that they are significantly disturbed by humans and have high ecological risk levels. The loss degree of cultivated land, forest land, and grassland shows small fluctuations and almost no change. The loss degree of water areas increases slightly. The loss degree of unused land and construction land shows a decreasing trend.

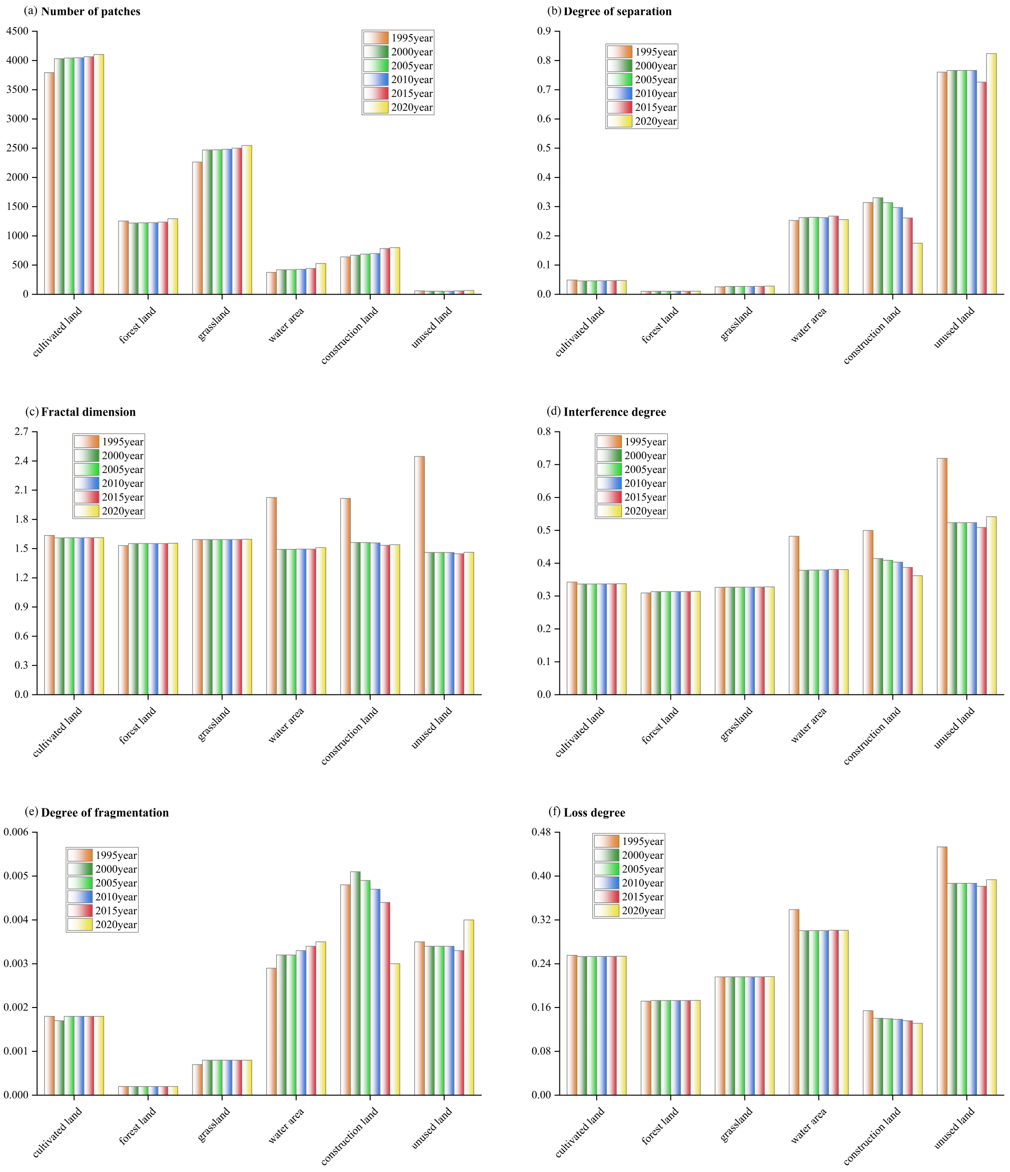

Figure 5. Landscape pattern index of various types in the Central Yunnan urban agglomeration from 1995 to 2020.

3.3. Spatiotemporal Changes in Landscape Pattern Ecological Risks

By calculating the ecological risk values for each risk area in various years and assigning them to the central points of each risk area, Kriging interpolation was applied to the central point data. Following the method of natural break classification, the landscape ecological risk results were categorized into five levels [39–41]: low (ERI < 0.1373), lower (0.1373 < ERI < 0.1595), medium (0.1595 < ERI < 0.1726), higher (0.1726 < ERI < 0.1850), and high (ERI > 0.1850). The ecological risk classification for other years was based on the classification intervals established in the year 2000 for ease of later data comparisons.

From 1995 to 2020, the Central Yunnan urban agglomeration was primarily composed of medium-ecological-risk areas, higher-ecological-risk areas, and high-ecological-risk areas. These three categories collectively accounted for over 77% of the study area's total area (Figure 6). Among them, higher-ecological-risk areas were the most prevalent, covering more than 28% of the total study area, followed by medium-ecological-risk areas, which accounted for over 24% of the entire study area. High-ecological-risk areas occupied more than 23% of the study area, while low-ecological-risk areas constituted less than 2% of the total area. The high-ecological-risk areas exhibited an initial increase followed by a subsequent decrease. Spatially, the low-ecological-risk areas are primarily concentrated near Dianchi Lake, while the lower-ecological-risk areas are mainly found in the Chuxiong Yi Autonomous Prefecture. The reason behind this distribution is that these regions are predominantly composed of forestland and grassland, characterized by higher elevations, numerous mountain ranges, and higher vegetation cover. Consequently, the degree of landscape fragmentation is lower, and the ecological environment is better. Mountains and forests play a crucial role in soil protection, climate regulation, and maintaining water sources, thereby reducing the probability of ecological risk occurrence. Regions with higher-ecological-risk and high-ecological-risk areas are predominantly centered in Qujing City and Kunming City. On the one hand, both Qujing and Kunming are major cities in Yunnan Province that have undergone rapid urbanization and population growth in recent years. During the urbanization process, extensive land development and construction activities can lead to ecosystem degradation. Population growth also exerts greater pressure on water resources, land use, and energy consumption, increasing the burden on the carrying capacity of ecosystems and exacerbating ecological risks. On the other hand, as these areas are economic and transportation hubs, the development of industry and transportation in Qujing and Kunming puts significant pressure on the ecological environment. Industrial activities generate substantial air, water, and solid waste pollutants, impacting the quality of the air, water bodies, and soil. Simultaneously, the development of transportation leads to road and infrastructure construction, causing changes in land use and ecosystem fragmentation, disrupting biodiversity and the ecological balance.

Throughout the study period, various ecological risk levels underwent constant transformations, resulting in changes in the areas of different ecological risk levels in 2020 (Figure 7). Many lower-ecological-risk areas were transferred to medium-ecological-risk areas, resulting in a decrease of 3.9% in lower-ecological-risk areas compared with 1995; medium-ecological-risk areas and high-ecological-risk areas were transferred in significant amounts to higher-ecological-risk areas, and higher-ecological-risk areas were transferred to higher-ecological-risk areas. The risk area increased by 3.9% compared with 1995, while the medium-ecological-risk area decreased by 0.7%; the higher-ecological-risk area was partially converted to a high-ecological-risk area, causing the high-ecological-risk area to increase by 0.4%. Over the entire period, the high-ecological-risk zone exhibits a trend of an initial expansion followed by a subsequent reduction. This suggests that certain ecological conservation measures have led to some improvements in the ecological environment within the high-ecological-risk zone. However, it is crucial to note that the damage inflicted upon the ecological environment is irreversible, making it difficult to achieve recovery once such damage has occurred.

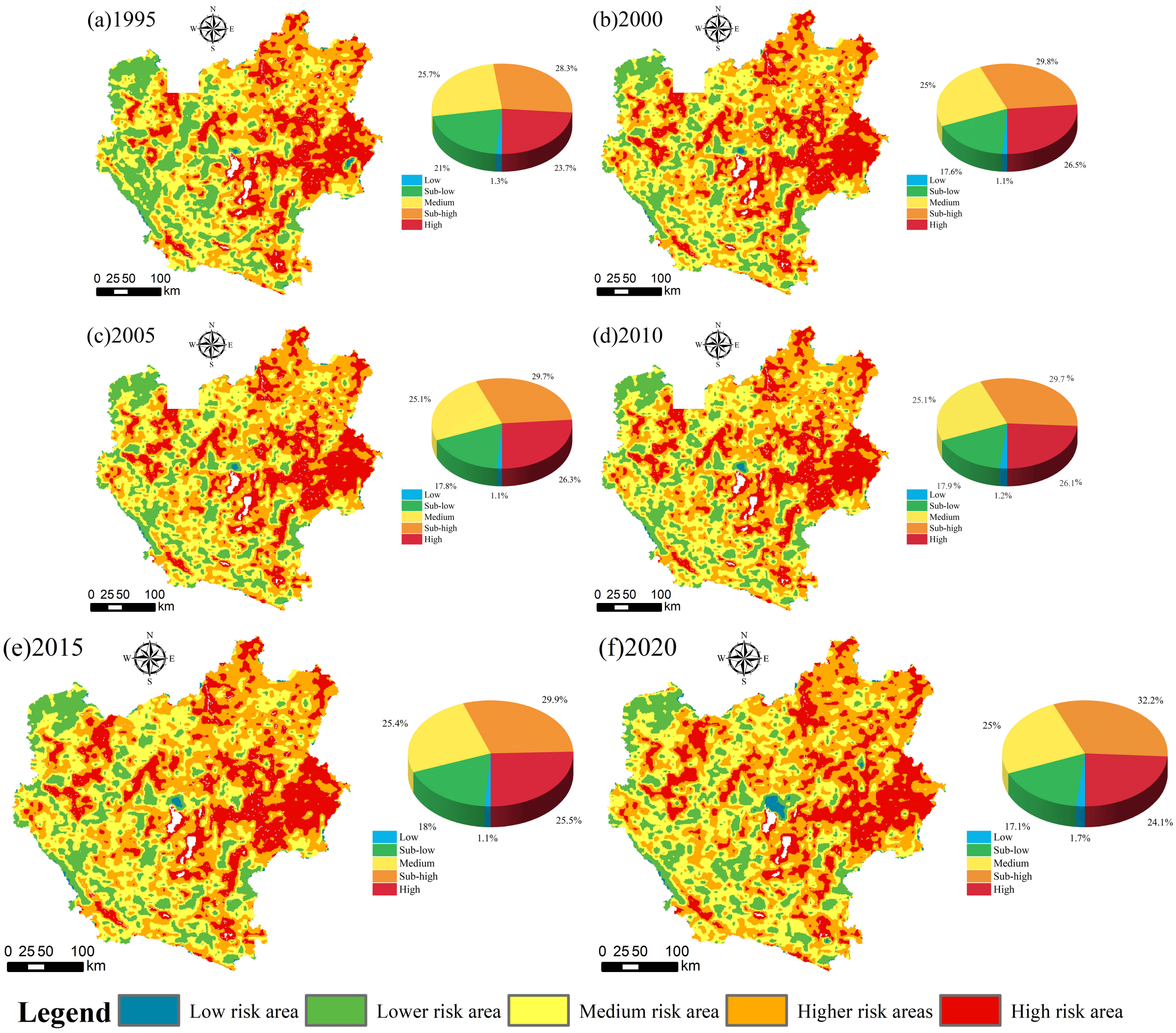

Figure 6. Distribution and percentage of landscape ecological risks in the Central Yunnan urban agglomeration from 1995 to 2020.

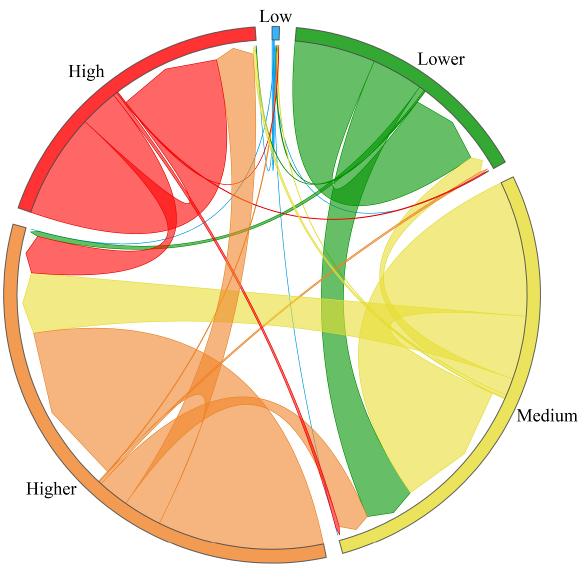

Figure 7. Chord diagram of landscape ecological risk transfer in the Central Yunnan urban agglomeration from 1995 to 2020.

3.4. Spatial Autocorrelation Analysis of Landscape Ecological Risks

Using GeoDa 1.2 software, we conducted a spatial global autocorrelation analysis of landscape ecological risk in the Central Yunnan urban agglomeration and obtained global *Moran's I* values (Figure 8). Figure 8 shows that the global *Moran's I* values for landscape ecological risk in the Central Yunnan urban agglomeration during the six periods were 0.311, 0.322, 0.300, 0.319, 0.315, and 0.296. These values indicate a pronounced positive spatial correlation of landscape ecological risk within the study area [42]. The global *Moran's I* exhibited an initial increase followed by a subsequent decrease, but all are positive values, suggesting the spatial clustering effects of landscape ecological risk in the Central Yunnan urban agglomeration.

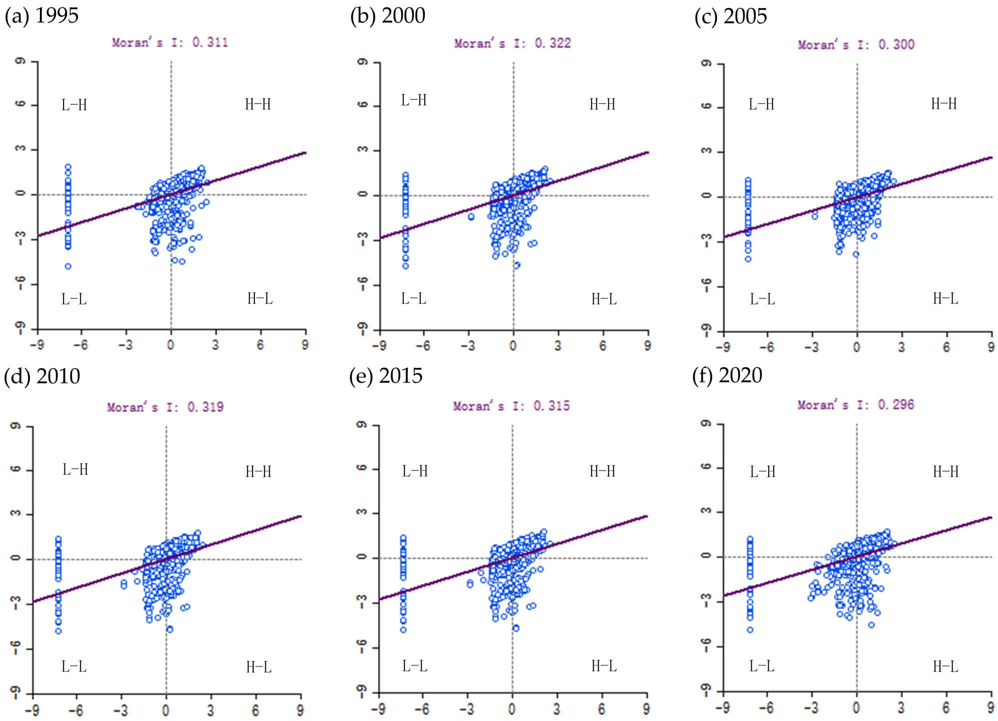

Figure 8. Moran's scatter plot of landscape ecological risks in the Central Yunnan urban agglomeration from 1995 to 2020.

Utilizing the LISA index to conduct a local spatial autocorrelation analysis of landscape ecological risk in the Central Yunnan urban agglomeration resulted in a LISA cluster map (Table 3, Figure 9). From Table 3 and Figure 9, it is evident that the local spatial distribution of landscape ecological risk in the Central Yunnan urban agglomeration from 1995 to 2020 is primarily characterized by "high–high" (H–H) and "low–low" (L–L) cluster areas, with "low–high" (L–H) and "high–low" (H–L) spatial distributions constituting a relatively small proportion of them. Between 2000 and 2015, the "low–high" (L–H) cluster areas exhibited a continuous increasing trend, while the "high–high" (H–H) cluster areas showed a persistent decreasing trend. In terms of the local spatial autocorrelation distribution characteristics, the "high–high" (H–H) cluster areas are primarily located in Qujing City. This region has a complex topography, dominated by mountains and hills, which may be significantly influenced by natural environmental factors. Additionally, human disturbances have led to a fragmented landscape distribution, resulting in high ecological risk aggregation levels. On the other hand, the "low–low" (L–L) cluster areas are predominantly found in the Chuxiong Yi Autonomous Prefecture and Yuxi City. These areas feature higher elevations, numerous mountain ranges, and a higher forest coverage rate, contributing to a relatively favorable ecological environment. Mountains and forests play a crucial role in soil protection, climate regulation, and water source maintenance, resulting in a lower aggregation of ecological risk.

Table 3. Proportion of urban agglomeration types in Central Yunnan from 1995 to 2020.

Year	Agglomeration Type				
	Non-Significant	**Low–Low**	**Low–High**	**High–Low**	**High–High**
1995	3698	273	27	64	647
2000	3672	307	26	51	653
2005	3687	301	30	50	641
2010	3692	301	31	52	633
2015	3096	303	32	52	626
2020	3811	225	28	53	592

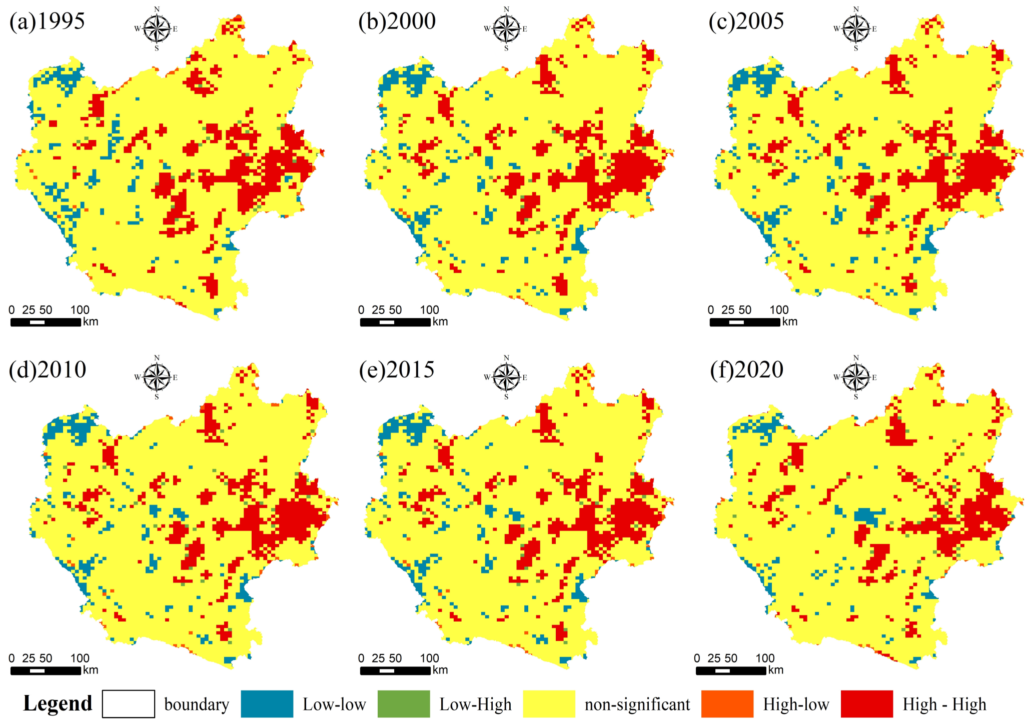

Figure 9. Distribution map of the local autocorrelation of landscape ecological risks in the Central Yunnan urban agglomeration from 1995 to 2020.

4. Discussion

The utilization of land-use change to assess landscape ecological risk represents a rapid and efficient approach to evaluating the spatiotemporal distribution and evolution characteristics of regional landscape features [43]. This assessment method has been widely used [44–46]. Assessing landscape ecological risk constitutes a key tool in maintaining ecosystem health, preserving natural resources, and achieving sustainable development. It allows for a comprehensive consideration of the impact of human activities on the environment, fostering improved protection and management of the natural environment, which is critical for our survival. By constructing a model for evaluating landscape ecological risk related to land use, this study comprehensively assesses the spatiotemporal dynamic changes in ecological risk within the Central Yunnan urban agglomeration from 1995 to 2020.

4.1. Analysis of Changes in Land Use

Based on a temporal analysis, land-use changes in the Central Yunnan urban agglomeration were rapid during two specific periods: 1995–2000 and 2015–2020. Examining the spatial distribution, the entire Central Yunnan urban agglomeration displays significant regional spatial heterogeneity in land-use changes. Over the past 25 years, economically thriving cities such as Kunming and Qujing experienced a swift expansion in construction land, resulting in substantial and drastic changes in land use. Other land-use types demonstrated a notable transition toward construction land, with its area experiencing a particularly evident increase. Conversely, less economically developed cities, such as the Chuxiong Yi Autonomous Prefecture, witnessed a slower expansion in construction land. This trend corresponds with findings from previous research [47]. In general, the region has experienced rapid economic development and an accelerated urbanization process [48] over the past twenty-five years. This has led to a substantial demand for construction land to support urban expansion and industrial development, prompted by a significant population influx, requiring extensive residential and urban infrastructure. These factors have led to increased demand for construction land, exacerbating the conversion of cultivated land, forest land, and grassland into construction land.

4.2. Analysis of Changes in Landscape Ecological Risk

Landscape ecological risk is closely associated with landscape pattern indices such as patch number, landscape fragmentation, and landscape isolation [49]. From the overarching perspective of the study, the landscape pattern exhibits relatively weak resistance to external disturbances, with the patch number increasing annually. This is attributed to the continuous intensification of human activities, resulting in the mutual conversion of land-use categories and alterations in the distribution patterns of the landscape. Formerly contiguous blocks are now divided into multiple discrete patches. From a temporal perspective, the overall ecological risk level in the research area exhibits an ascending trend. The proportions of higher and high levels of ecological risk consistently increased in the periods 1995–2000 and 2015–2020, while gradually decreasing between 2000 and 2015, in line with the outcomes of land-use changes. The predominant ecological risk level in the research area is higher ecological risk, displaying an increasing trend, whereas high-ecological-risk areas show an initial increase followed by a subsequent decrease. Over the 25-year period from 1995 to 2020, rapid urban expansion and the swift development of the economy and the tourism industry have led to environmental degradation. In response to the recognition of environmental issues, the government has placed significant emphasis on environmental protection, enacting a series of policies related to land use, which have, to some extent, improved the current quality of the ecological environment [31]. Simultaneously, technology is advancing continuously, and the development of advanced environmental protection and clean energy technologies makes environmental conservation more feasible and economically viable. This progress enables a reduction in pollutant emissions and enhances resource utilization efficiency, thereby improving the quality of the ecological environment. Spatially, higher-ecological-risk areas and high-ecological-risk areas are predominantly concentrated in Kunming City and Qujing City. The aggregation effect of landscape ecological risk is significant in spatial terms, with "high–high" (H–H) and "low–low" (L–L) clustering being the main local autocorrelation patterns. "High–high" (H–H) clustering is mainly distributed in economically developed regions such as Kunming City and Qujing City, which experience significant disturbance due to human activity; other land-use types are prone to conversion into construction land. On the other hand, "low–low" (L–L) clustering is mainly found in areas with high levels of vegetation coverage, such as Yuxi City and the Chuxiong Yi Autonomous Prefecture. Vegetation coverage can influence regional landscape patterns and functions [50], with higher levels of vegetation coverage enhancing resistance to disturbances and promoting regional sustainability. It is evident that there is a close connection between landscape ecological risk and land-use types.

4.3. Suggestions for Ecological Risk Prevention and Control in the Central Yunnan Urban Agglomeration

Based on its analysis of landscape ecological risk in the Central Yunnan urban agglomeration, this study offers the following recommendations concerning different risk levels. For high-ecological-risk areas and moderate-to-high-ecological-risk areas, stringent environmental policies should be implemented. Ecological plans that delineate the boundaries of protected areas and vital ecological functional zones should be developed, and land-use management should be improved to ensure a rational land-use layout, with appropriate allocations for construction and conservation purposes, thereby minimizing damage to critical ecosystems. Protection and restoration efforts should be enhanced for ecosystems, particularly in important ecological functional zones and ecologically sensitive areas. In urban planning, the construction of green infrastructure should be promoted, such as green belts and urban parks. For areas with low, lower, and medium ecological risk levels, it is essential to establish a robust environmental monitoring and assessment system. This system should facilitate the timely monitoring and assessment of the impact of urban expansion on the ecological environment. Supported by scientific data, it would enable the prompt identification of issues and risks, allowing for the implementation of corresponding management and control measures. Adopting this proactive strategy will contribute to averting the transformation of ecological risk areas into higher-risk classifications.

5. Conclusions

Considering the drastic changes in land use/cover, evaluating landscape ecological risk can improve efforts to better coordinate risk prevention, continuously improve the quality of the ecological environment, and promote green transformations in economic and social development; such evaluations are important for formulating comprehensive and scientifically sound policies for the Central Yunnan urban agglomeration and constructing a vital ecological barrier in the southwestern region. Based on land-use raster data from the Central Yunnan urban agglomeration from 1995 to 2020, this study employs GIS technology to assess landscape ecological risks in the region. By conducting a comprehensive analysis of land-use changes and transitions, spatiotemporal variations in landscape patterns of ecological risk, and the spatial autocorrelation of landscape ecological risk in the Central Yunnan urban agglomeration, the following conclusions were drawn.

First of all, the predominant land-use types in the Central Yunnan urban agglomeration were forest land, grassland, and cultivated land, accounting for approximately 48%, 26%, and 18% of the total land area in each year, respectively. During the study period, the years 1995–2000 and 2015–2020 experienced the highest conversion intensity. Cultivated land, forest land, and grassland are experiencing a decline in area, whereas water areas and construction land are witnessing an upward trend. Notably, cultivated land, grassland, and construction land experienced significant changes, with the expansion of construction land being the most pronounced. This expansion primarily resulted from the conversion of cultivated land, forest land, and grassland. Then, there were significant spatial variations in the distribution of ecological risk within the Central Yunnan urban agglomeration. Overall, the region was predominantly characterized by medium-ecological-risk areas, sub-high-ecological-risk areas, and high-ecological-risk areas, collectively accounting for over 77% of the study area. Among these, grassland was the dominant landscape type in areas with medium levels of ecological risk, while cultivated land and construction land were prevalent in regions with sub-high and high levels of ecological risk. In terms of spatial distribution, areas with relatively low levels of ecological risk were mainly concentrated in the Chuxiong Yi Autonomous Prefecture. Conversely, regions with relatively high and high levels of ecological risk were primarily concentrated in Qujing City and Kunming City. Finally, the global *Moran's I* values for landscape ecological risk in the research area were consistently around 0.3, indicating the strong positive spatial autocorrelation of landscape ecological risk within the region. The local spatial distribution of landscape ecological risk was predominantly characterized by "high–high" (H–H) and "low–low" (L–L) clustering areas, with a relatively small proportion of "low–high" (L–H) and "high–low" (H–L) spatial distributions. Based on an analysis of the local spatial autocorrelation characteristics, the "high–high" (H–H) clustering areas were mainly concentrated in Qujing City, while the "low–low" (L–L) clustering areas were primarily located in the Chuxiong Yi Autonomous Prefecture and Yuxi City.

Based on the landscape ecological risk assessment and spatial pattern evolution analysis of the Central Yunnan urban agglomeration's land use/cover from 1995 to 2020, understanding the spatiotemporal variations in landscape ecological risk and its spatial differentiation is crucial for undertaking rational and scientific land-use planning in the Central Yunnan urban agglomeration. This is essential for reducing ecological risk and is highly important to achieving sustainable development in this research area. However, this study has some limitations. Firstly, there is some subjectivity in the classification of risk levels, and these grading outcomes might not completely represent the truth of the situation within the region. The spatial resolution of the land-use data used in this paper is 1 km × 1 km. In the next step, considering land-use data with a spatial resolution of 30 m and higher precision for long-term sequences will provide a more detailed portrayal of changes in landscape ecological risk in the research area. Moreover, the study did not account for future land use predictions under multiple scenarios. Utilizing the PLUS [51] model to forecast land use under various scenarios can help us assess the spatiotemporal evolution of landscape ecological risk, thereby deriving the optimal development scenarios.

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