

Article

Peri-Urban Agroforestry Landscapes Under Pressure: Ecological Risks Amid Rapid Urbanization—A Case Study of Pidū District, Southwest China

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Abstract

Rapid urbanization has been associated with substantial structural adjustments and ecological risks in peri-urban agroforestry landscapes. Taking Pidū District, Chengdu, China, as a representative peri-urban region, this study investigated the spatiotemporal evolution of agroforestry landscapes and their ecological risks from 2000 to 2020. Utilizing multi-period land-use data, we integrated landscape pattern indices, an ecological risk assessment model, etc. The results showed that the agroforestry landscape area decreased by 24.53%, from 275.39 km² to 207.83 km², a decline primarily tied to the expansion of construction land. Ecological risk increased continuously over the study period, with high-risk areas concentrated in the rapidly urbanizing southern region and low-risk areas mainly distributed in the northern agricultural zone. Meanwhile, landscape fragmentation intensified, as reflected by increasing patch subdivision and declining landscape integrity. Bivariate spatial autocorrelation analysis revealed a positive spatial association between fragmentation and ecological risk, indicating that structural degradation of agroforestry landscapes is an important factor of ecological risk escalation. Overall, rapid urbanization in Pidū District was accompanied by the coupled processes of agroforestry landscape shrinkage, fragmentation, and ecological risk growth. These findings provide scientific support for ecological risk zoning management and agroforestry landscape conservation in similar rapidly urbanizing regions.

Keywords: peri-urban areas; agroforestry landscapes; ecological risk; landscape fragmentation; urbanization; land-use change; landscape ecology



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1. Introduction

Urbanization, as one of the primary drivers of global environmental change, is profoundly reshaping land-use patterns and ecosystem service functions [1]. According to estimates by the United Nations, nearly 70% of the global population will reside in urban areas by 2050, and the pressure exerted by urban expansion on natural and semi-natural ecosystems is expected to intensify further [2]. During rapid urbanization, the encroachment of construction land on agricultural and ecological spaces has contributed to a series of cascading ecological effects, including intensified land-use conflicts, increased landscape fragmentation, and the accumulation of ecological risks [3]. In particular, peri-urban areas—transitional zones linking urban built-up areas with surrounding agricultural

hinterlands—experience the most intensive land-use conversion and concentrated human–land conflicts, making them a focal topic in landscape ecology and regional sustainable development research [4].

Peri-urban areas possess both urban influences and rural characteristics. As key providers of regional ecosystem services, their agroforestry landscapes are facing unprecedented spatial compression [5] and increasing pressure from structural reorganization. Agroforestry landscapes are composite systems in which agricultural production spaces and natural ecological spaces are interwoven, integrating multiple production, ecological, and cultural functions [6]. Within the framework of landscape ecology, the patch structure, corridor connectivity, and matrix characteristics of agroforestry landscapes jointly determine their ecological stability and resilience to disturbance, thereby providing an important foundation for maintaining regional biodiversity and ecosystem services [7,8]. With the continued acceleration of global urbanization, the conservation and management of agroforestry landscapes have gradually become central concerns in landscape ecology and land-use science.

During rapid urbanization, large areas of agroforestry landscapes in peri-urban regions, particularly cropland and forestland, have been converted into impervious surfaces and artificial structures. Such land-use changes disrupt landscape connectivity, weaken ecosystem service functions, and consequently increase ecological risks. Based on the HILDA+ dataset, Woodman et al. [9] found that the fragmentation of cropland and forestland worldwide intensified between 1992 and 2020, with particularly pronounced changes occurring in peri-urban transitional zones. The continuous decline in landscape connectivity directly reduced the capacity of regional ecosystems to provide services. Using the urban–rural fringe of northern Italy as a case study, Smiraglia et al. [10] systematically examined the differentiated impacts of urban expansion and agricultural intensification on agroforestry landscape structure through a long-term comparison from 1954 to 2008 and reported a clear trend of landscape degradation. Similarly, Han et al. [11] demonstrated that the ecological functions of agroforestry landscapes vary significantly across different topographic settings. In plain agricultural regions, where such landscapes are relatively continuous, urban encroachment often results in more substantial losses of ecological integrity. Cheng et al. [12] further demonstrated that land-use change and the resulting landscape fragmentation are important drivers of regional ecological risk. The encroachment and fragmentation of cropland and forestland caused by urban expansion can increase the extent of high-risk ecological areas, whereas the protection and restoration of fragmented peri-urban cropland and forestland can help mitigate landscape ecological risk. Seto et al. [2] also projected that by 2030, global urban expansion will replace large areas of natural and semi-natural landscapes in peri-urban regions with construction land, highlighting the growing concern over agroforestry landscape loss and the associated degradation of ecological functions.

Against this background, methods for landscape ecological risk assessment have gradually evolved. Peng et al. [13] systematically reviewed the conceptual framework of landscape ecological risk assessment and proposed an evaluation model based on two dimensions: landscape disturbance and landscape vulnerability. Wang et al. [14] and Li et al. [15] subsequently verified the applicability of this framework at watershed and regional scales, respectively. Ecological risk assessment models incorporating landscape pattern indices have since been widely applied across multiple spatial scales, including provinces, large river basins, and urban agglomerations [16–19], providing effective tools for quantifying ecological risks associated with land-use change.

Overall, peri-urban areas have long been spatial units where agroforestry landscapes are highly exposed to urbanization pressures and where landscape pattern changes are

particularly pronounced. Moreover, structural changes in agroforestry landscapes are closely associated with the spatial distribution of ecological risk. Increased landscape fragmentation is often accompanied by greater ecological vulnerability, and peri-urban regions represent the areas where this process is most evident. However, existing studies remain limited in their integrated examination of agroforestry landscape evolution and ecological risk responses in peri-urban settings [20].

Based on these considerations, this study selects Pidū District, Chengdu, China, as the study area. Located in the hinterland of the Chengdu Plain, Pidū District lies at the intersection of the core area of the Dujiangyan Irrigation System and the functional spillover zone of central Chengdu [21]. It not only exhibits the characteristics of a peri-urban transitional region but also preserves the traditional agroforestry landscape pattern of the Western Sichuan Plain, making it a representative case of peri-urban agroforestry landscapes. However, since the beginning of the twenty-first century, alongside the transformation of Chengdu's urban spatial structure from a monocentric to a polycentric pattern, Pidū District has experienced rapid expansion of construction land and continuous contraction of agroforestry landscapes. Consequently, the conflict between agroforestry landscape conservation and urban development has become increasingly prominent. Therefore, the dynamic changes in agroforestry landscapes under rapid urbanization and their ecological risk implications constitute the central focus of this study.

In summary, this study hypothesizes that rapid urbanization is accompanied by substantial changes in land-use composition and agroforestry landscape configuration, which are expected to be associated with changes in landscape fragmentation and the spatial distribution of landscape ecological risk. Using land-use data from 2000, 2010, and 2020, this study employs bivariate spatial autocorrelation analysis, landscape pattern indices, and a landscape ecological risk assessment model to investigate land-use change, structural evolution of agroforestry landscapes, ecological risk responses, and landscape fragmentation under rapid urbanization in Pidū District, Chengdu, China. The study aims to examine the associations between agroforestry landscape restructuring, ecological risk evolution, and landscape fragmentation. Specifically, it focuses on three aspects: (1) identifying the spatiotemporal evolution of cropland, forestland, and other land-use types during urban expansion and revealing the spatial distribution and changing patterns of agroforestry landscapes; (2) constructing a landscape ecological risk assessment model to evaluate ecological risk levels, characterize their spatial differentiation, and identify ecological risk hotspots in Pidū District; and (3) assessing agroforestry landscape fragmentation using landscape pattern indices, examining its structural evolution, and exploring its spatial relationship with ecological risk. This study contributes to a deeper understanding of the interactions among agroforestry landscape evolution, fragmentation, and ecological risk under rapid urbanization. The findings provide a theoretical foundation and practical reference for agroforestry landscape conservation, ecological risk management, and territorial spatial optimization in similar peri-urban regions while also supporting efforts to alleviate ecological pressures associated with urban expansion and promote regional ecological security and sustainable development.

2. Materials and Methods

2.1. Study Area

Pidū District is located in northwestern Chengdu, within the hinterland of the Western Sichuan Plain, China. It extends between 103°42'–104°02' E and 30°43'–30°52' N and covers a total area of approximately 433 km². As shown in Figure 1, the study area is characterized by a flat terrain, with elevations ranging from 520 to 630 m, and a subtropical humid monsoon climate. An extensive river network supports the traditional agroforestry

landscape of the Western Sichuan Plain, making the district one of Chengdu's major agricultural production bases and an important component of its peri-urban ecological zone. The southern part of the district has experienced continuous urban expansion in response to its proximity to central Chengdu, accompanied by rapid urbanization and substantial growth of construction land. In contrast, the northern part retains relatively intact agricultural landscapes and the traditional Linpan settlement system (rural agroforestry settlements in Western Sichuan, China, hereafter referred to as Linpan). The permanent resident population exceeded one million in both 2000 and 2020, and the urbanization rate reached 79.83% by 2020. Under the combined influences of intensive agricultural activities and sustained urbanization pressure, Pidu District provides a representative case for investigating the evolution of agroforestry landscapes and their ecological responses in peri-urban areas.

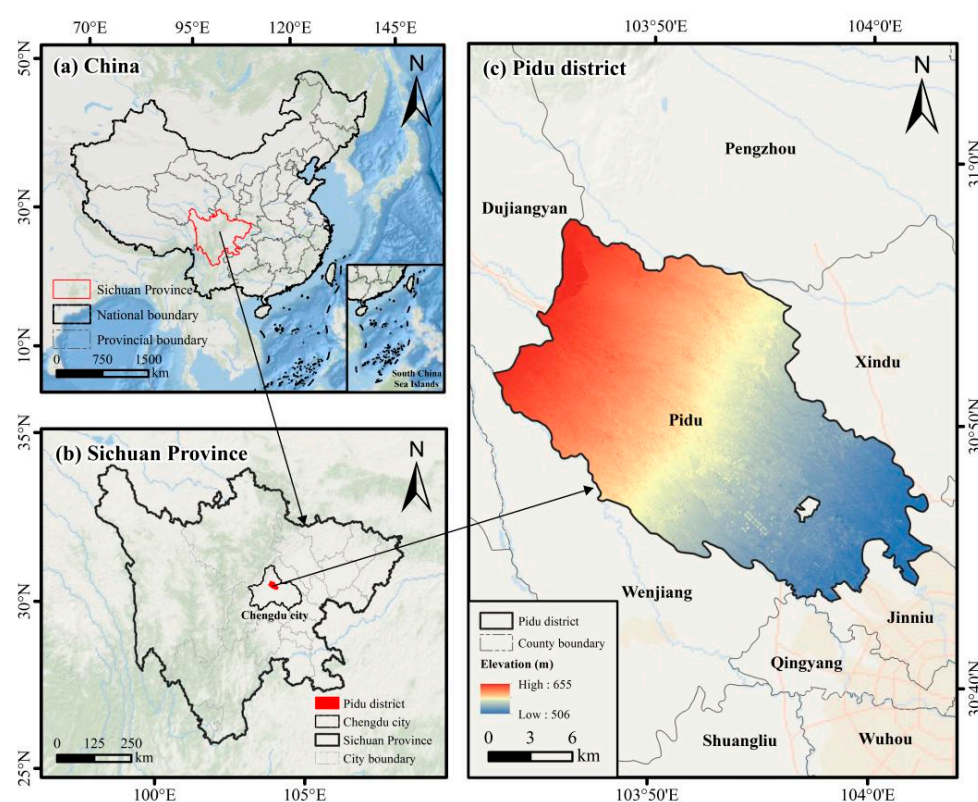


Figure 1. Location map of the study area: (a) location of China; (b) location of Sichuan Province and Chengdu City; (c) geographical location of Pidu District.

2.2. Data Sources

Land-use data for the study area in 2000, 2010, and 2020 were obtained from the China Multi-period Land Use Remote Sensing Monitoring Dataset (CNLUCC, <https://www.resdc.cn> (accessed on 29 November 2025)), provided by the Resource and Environment Science and Data Center, Chinese Academy of Sciences. The dataset is derived from Landsat remote sensing imagery with a spatial resolution of 30 m and is widely used for regional-scale landscape pattern analysis. According to the Current Land Use Classification standard of China and the local conditions of Pidu District, the original land-use categories were reclassified into four types: cropland, forestland, water bodies, and construction land. Administrative boundary data were obtained from the National Catalogue Service for Geographic Information (<https://mulu.tianditu.gov.cn/> (accessed on 15 July 2026)). To ensure spatial consistency and the reliability of area- and distance-based calculations, all spatial datasets were projected to the WGS 1984 UTM Zone 48N-projected coordinate

system before analysis. This projected coordinate system uses meters as map units and is suitable for the study area in Chengdu, China.

2.3. Methods

This study constructed an analytical framework for agroforestry landscape evolution comprising four main components: data acquisition and preprocessing, agroforestry landscape identification, ecological risk assessment, and landscape fragmentation analysis (Figure 2). Multi-period land-use datasets were collected and preprocessed using ArcGIS 10.8. Next, a bivariate Local Indicators of Spatial Association (LISA) analysis implemented in GeoDa was conducted to characterize agroforestry landscape mosaics. An ecological risk assessment framework was established based on landscape disturbance and landscape fragility indices to assess regional ecological risk and its spatial patterns. Finally, landscape fragmentation characteristics of the identified agroforestry landscapes were quantified using multiple landscape metrics, and the spatial association between agroforestry landscape fragmentation and ecological risk was further examined. Detailed methods and calculation procedures are provided in Sections 2.3.1–2.3.3.

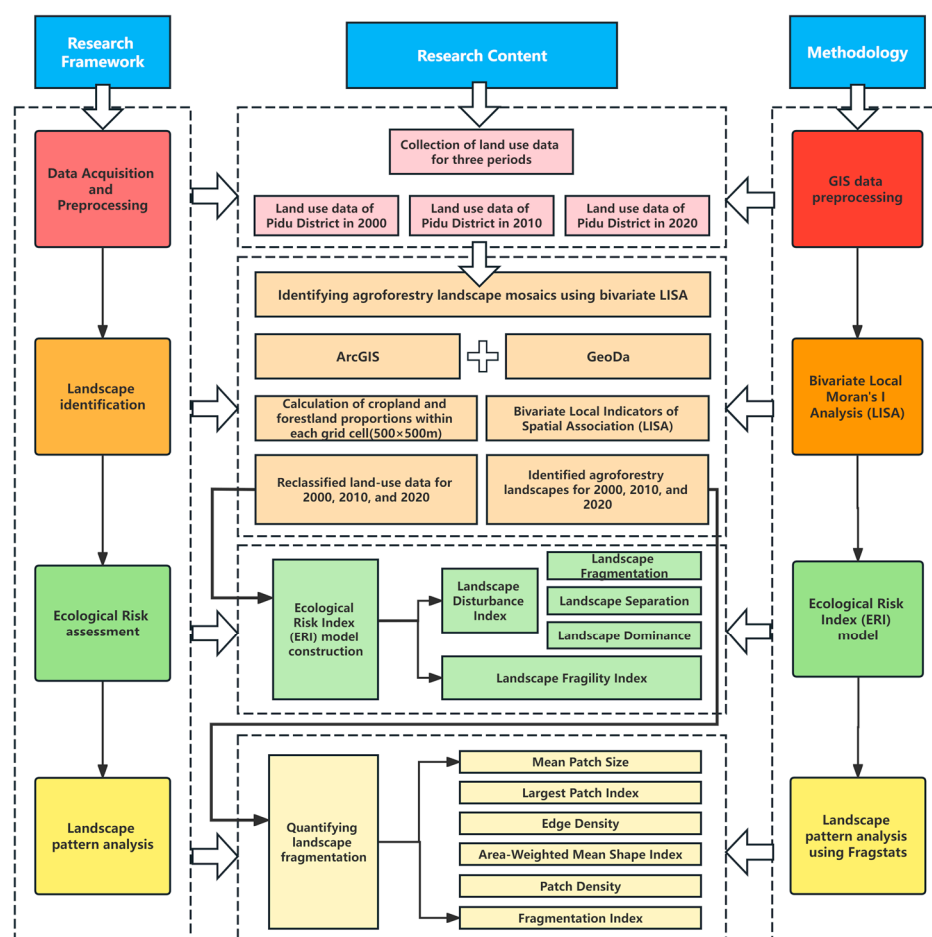


Figure 2. The analytical framework for agroforestry landscapes.

2.3.1. The Identification of Agroforestry Landscapes

To objectively delineate the spatial extent of cropland–forest landscape mosaics (hereafter referred to as agroforestry landscapes) in Pidū District and reduce potential bias associated with using administrative boundaries or single land-use types as proxies, this study adapted the identification framework for forest–grassland ecotones proposed by Guo et al. [22]. A bivariate Local Moran’s I (bivariate local spatial autocorrelation) approach

was employed to identify statistically significant spatial associations between cropland and forestland proportions and characterize their spatial co-occurrence patterns. First, a regular 500 m × 500 m grid was generated across the entire study area [23,24], and the area proportions of cropland and forestland were calculated for each grid cell. Next, GeoDa 1.22 software was used to compute the bivariate Local Moran's I between cropland and forestland proportions, and three cluster types (High–High, High–Low, and Low–High) were identified to represent different spatial configurations where cropland and forestland co-exist. Crucially, this classification assigns a landscape mosaic label to each 500 m × 500 m grid cell based on the proportional composition of the two underlying land-use types. Consequently, no spatial units are double-counted. Finally, the classification results from different periods were overlaid to generate a dynamic map of agroforestry landscape extent for the period 2000–2020.

2.3.2. Landscape Ecological Risk Assessment

Based on the 500 m × 500 m grid units established above, the comprehensive ecological risk index (ERI) was calculated for each unit to spatially characterize ecological risk. For each ecological risk assessment unit, the ERI was calculated at the landscape level by integrating all land-use categories, thereby representing the overall ecological risk of the entire landscape rather than a single landscape type. Accordingly, an integrated ERI value representing the overall ecological risk of each assessment unit was obtained. Referring to the methodology reported by Zhang Xuebin et al. [25], the landscape ERI is formulated as follows:

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

where

ERI_k represents the ecological risk index of the k -th risk unit; A_{ki} represents the area of the i -th landscape type within the k -th risk unit; A_k represents the total area of the k -th risk unit; and R_i represents the landscape loss index of the i -th landscape type.

The landscape loss index R_i is jointly determined by the landscape disturbance index E_i and the landscape fragility index F_i :

$$R_i = E_i \times F_i \quad (2)$$

F_i in the study area is divided into five grades; the values were assigned based on the study by Liu et al. [26]. Water bodies were considered the most vulnerable due to their high sensitivity to external disturbances and pollution, followed by cropland, which is subject to intensive human management and frequent disturbance. Forestland generally exhibits stronger ecological stability and self-regulation capacity than cropland, whereas construction land was assigned the lowest vulnerability value because it represents a highly artificial landscape component with limited ecological sensitivity within this framework. Agroforestry landscape was assigned an intermediate value between cropland and forestland, reflecting their mixed characteristics of agricultural dependence and enhanced ecological stability provided by forest components. Accordingly, the F_i values were ranked in descending order: water bodies, cropland, agroforestry landscapes, forestland and construction land. The landscape vulnerability index F_i of each landscape type is obtained after normalization.

The landscape disturbance index E_i quantifies the degree of external disturbance imposed on each landscape type, and is calculated as follows:

$$E_i = aC_i + bN_i + cD_i \quad (3)$$

where

C_i represents the landscape fragmentation index, $C_i = n_i / A_i$;

N_i represents the landscape separation index, $N_i = \frac{A}{2A_i} \sqrt{\frac{n_i}{A}}$;

n_i refers to the number of patches of landscape type i . A_i represents the total area of landscape type i , and A denotes the total landscape area;

D_i represents landscape dominance, calculated comprehensively based on patch frequency and area proportion;

a, b, c are weighting coefficients, assigned values of 0.5, 0.3, and 0.2 [27], respectively.

2.3.3. Fragmentation Evaluation

In this part, fragmentation analysis was conducted independently from the ecological risk assessment and focused exclusively on agroforestry landscape patches. To characterize the fragmentation characteristics of agroforestry landscapes, six landscape pattern metrics representing three dimensions (size, shape, and spatial distribution) were selected to construct the evaluation index system for agroforestry landscape fragmentation. The calculation formulas and directional attributes of each metric are provided in Table 1. Fragmentation metrics were calculated using FRAGSTATS 4.2 based on the agroforestry landscape patches identified in Section 2.3.1.

Table 1. Indicators for the calculation of agroforestry landscape fragmentation.

Indicator	Primary Indicator	Secondary Indicator	Calculation Method	Directional Attributes
Landscape fragmentation (CLFI)	Size fragmentation	Mean patch size (MPS)	$MPS = A/N$, A represents the total area of agroforestry landscapes, and N represents the number of agroforestry landscape patches	-
		Largest patch index (LPI)	$LPI = A_{max}/A$, A_{max} represents the maximum patch size, and A represents the total area of agroforestry landscapes	-
	Shape fragmentation	Edge density index (ED)	$ED = E/A$, E represents the total edge length of agroforestry landscapes, and, A represents the total area of agroforestry landscapes	+
		Area-weighted mean shape index (AWMSI)	$AWMSI = \sum_{i=1}^n [(0.25P_i / \sqrt{a_i})(a_i/A)]$, n represents the number of agroforestry landscape patches, P_i represents the number of agroforestry landscape patches, a_i represents the area of patch i , and A is the total area of agroforestry landscapes	+
	Distribution fragmentation	Patch density (PD)	$PD = n/A$, n represents the number of agroforestry landscape patches, and A represents the total area of agroforestry landscapes	+
		Fragmentation index (FS)	$FS = 1 - 1/MSI$, $MSI = \sum_{i=1}^n (0.25P_i / \sqrt{a_i}) / N$, a_i represents the patch size, P_i represents the patch size, N represents the number of agroforestry landscape patches	+

Secondly, the indicator weights used in this study were derived from an improved Fuzzy Analytic Hierarchy Process (FAHP)–Entropy weighting framework developed by Huang et al. [28], and are presented in Table 2. This hybrid weighting approach combines the subjective strengths of the FAHP with the objective properties of the entropy method,

thereby reducing potential biases associated with expert judgment or excessive reliance on raw data that may arise from single weighting techniques. Owing to its robustness and proven applicability, the framework has been widely used for regional landscape fragmentation assessment.

Table 2. Weights for agroforestry landscape fragmentation assessment.

Indicator	MPS	LPI	ED	AWMSI	PD	FS
Weight	0.14	0.18	0.15	0.23	0.14	0.16

3. Results

3.1. Identification of Agroforestry Landscapes

Using GeoDa software, a bivariate Local Moran's I (LISA) analysis was conducted to distinguish the heterogeneous spatial aggregation patterns of agroforestry landscapes [29]. The three cluster types—high–low, low–high, and high–high—represent different composite spatial relationships of agroforestry landscapes, corresponding respectively to cropland-dominated agroforestry landscapes, forestland-dominated agroforestry landscapes, and agroforestry-balanced landscapes (Table 3). Cropland-dominated agroforestry landscapes showed a decreasing trend over the past two decades, declining from 240.21 km² in 2000 to 170.07 km² in 2020, yet they remained the dominant type, indicating that most areas in Pidū District are still primarily characterized by agricultural cultivation with locally embedded forest patches. In contrast, agroforestry-balanced landscapes increased from 22.24 km² in 2000 to 30.55 km² in 2020. In terms of spatial distribution (Figure 3), balanced agroforestry landscapes were mainly concentrated in the northern traditional agricultural areas, where relatively intact Linpan systems and cropland–forest mosaic structures are preserved, forming a stable core zone of agroforestry landscapes. By comparison, forestland-dominated agroforestry landscapes showed a declining trend, decreasing from 13.27 km² to 7.49 km², and were mainly distributed along river corridors or at the edges of ecological conservation areas.

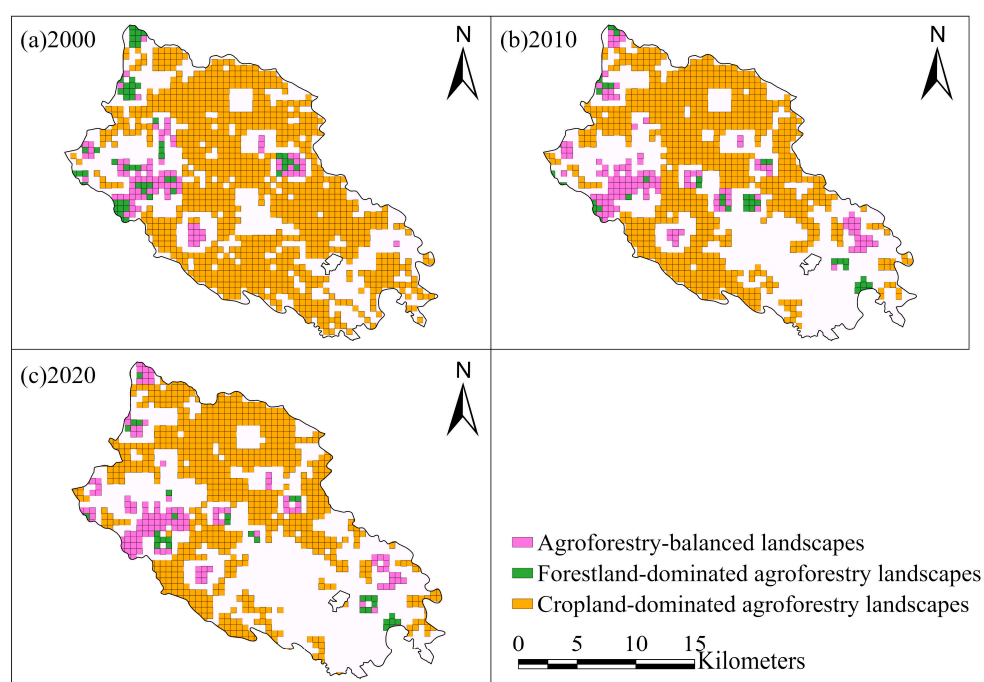


Figure 3. Spatial distribution pattern of different agroforestry landscapes in Pidū District: (a) 2000; (b) 2010; (c) 2020.

Table 3. Areas of different agroforestry landscapes in Pidú District from 2000 to 2020.

Agroforestry Class	Area (km ²)		
	2000	2010	2020
Agroforestry-balanced landscape	22.24	32.09	30.55
Forestland-dominated Agroforestry landscape	13.27	8.78	7.49
Cropland-dominated Agroforestry landscape	240.21	190.77	170.07

Overall, agroforestry landscapes in Pidú District are predominantly characterized by a “cropland-dominated with forest patches embedded” pattern. This is accompanied by a declining trend in forestland-dominated agroforestry landscapes and an increasing trend in agroforestry-balanced landscapes, indicating that the regional agroforestry landscape structure is shifting from a single dominant type toward a more balanced composition of multiple components. This evolution reflects progressively increasing cropland–forest integration and landscape heterogeneity.

3.2. Evolution of Land-Use Classes and Agroforestry Landscapes

To characterize the evolution of agroforestry landscapes within the regional land-use pattern, the three agroforestry landscape types were integrated and analyzed as a single land-use category. As shown in Table 4, the total area of agroforestry landscapes in the study area reached 275.39 km² in 2000, accounting for 63.6% of the total area (433.15 km²) and constituting the dominant landscape type in the region. By 2010, the area had declined to 231.66 km², representing 53.5% of the total area, and further decreased to 207.83 km² in 2020, accounting for only 48.0%. Over the 20-year study period, agroforestry landscapes experienced a net loss of 67.56 km², corresponding to a decline of 24.53%. Their dominant position was gradually eroded by the expansion of construction land and cropland. Notably, the reduction during 2000–2010 (43.73 km²) was substantially greater than that during 2010–2020 (23.83 km²), indicating that agroforestry landscapes were subjected to more intense encroachment during the initial stage of rapid urbanization.

Table 4. Areas and proportions of different land-use classes in Pidú District from 2000 to 2020 (unit: km²).

Class	Area (Proportion)		
	2000	2010	2020
Cropland	117.10 (27.04%)	95.13 (21.96%)	92.34 (21.32%)
Agroforestry	275.39 (63.58%)	231.66 (53.48%)	207.83 (47.98%)
Forest	1.52 (0.35%)	1.96 (0.45%)	2.32 (0.54%)
Construction land	38.67 (8.93%)	103.83 (23.97%)	129.69 (29.94%)
Water	0.44 (0.10%)	0.59 (0.14%)	0.98 (0.23%)
Total area		433.15	

Analysis of land-use transition pathways revealed that the loss of agroforestry landscapes was primarily associated with conversion to construction land and cropland. Over the study period, approximately 72.12 km² of agroforestry landscapes were transformed into construction land, while 45.10 km² were converted to cropland, indicating that urban expansion was the primary factor associated with agroforestry landscape shrinkage. During 2000–2010, the areas converted to construction land and cropland reached 48.39 km² and 25.16 km², respectively, whereas the corresponding values declined to 23.73 km² and

19.94 km² during 2010–2020, suggesting a gradual weakening of landscape conversion intensity. Spatially, the reduction in agroforestry landscapes exhibited a distinct pattern of “rapid change in the south and relative stability in the north”. As shown in Figure 4, in the southern part of the district, contiguous urban expansion associated with the development of central Chengdu occurred alongside the large-scale replacement of agroforestry landscapes by construction land. In contrast, although the northern region also experienced scattered encroachment by construction land, the overall agroforestry landscape matrix remained relatively intact.

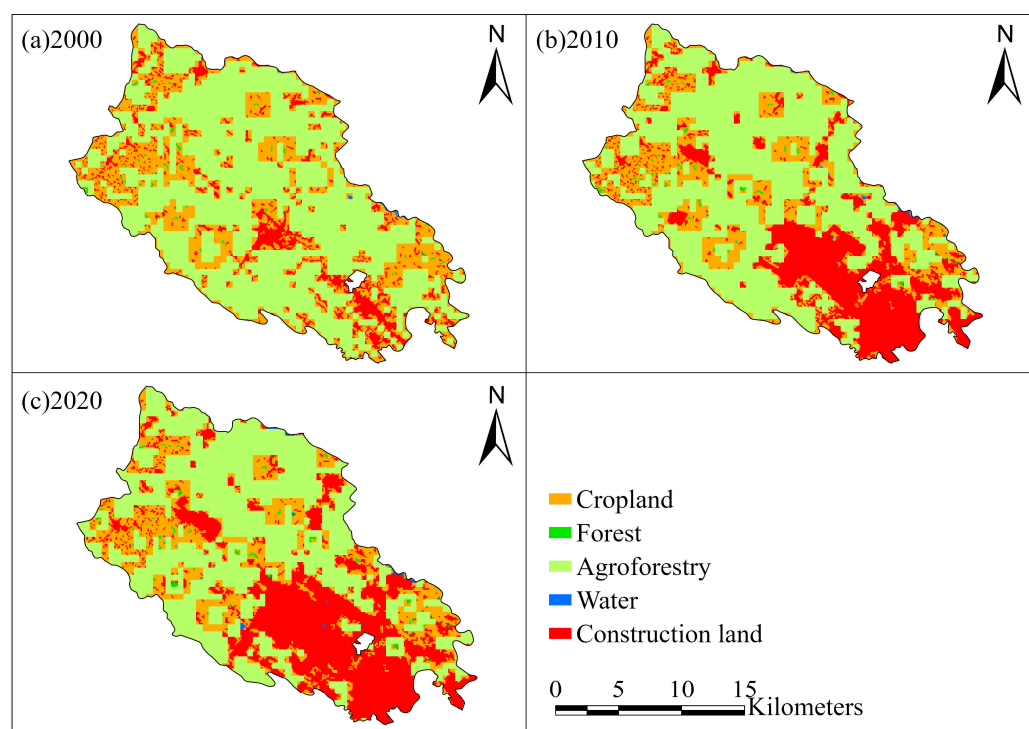


Figure 4. Spatial distribution pattern of land-use classes in Pidū District: (a) 2000; (b) 2010; (c) 2020.

3.3. Spatiotemporal Assessment of Landscape Ecological Risk

To facilitate the interpretation and visualization of the spatial heterogeneity of ecological risk, the ERI values were classified into five ecological risk levels (low, low–moderate, moderate, moderate–high, and high) using the Natural Breaks (Jenks) classification method implemented in ArcGIS. This data-driven classification approach identifies class boundaries according to the statistical distribution of ERI values by minimizing within-class variation and maximizing between-class differences, thereby preserving the inherent characteristics of the data rather than relying on predefined thresholds. Subsequently, ordinary kriging interpolation was employed to generate continuous spatial distribution maps of ecological risk, providing a visual representation of the spatial variation in ecological risk across Pidū District during the study period (Figure 5). Statistical analyses were further conducted for each risk category (Table 5), and ecological risk transition matrices were constructed for the periods 2000–2010 (Table 6) and 2010–2020 (Table 7) to reveal the temporal evolution and spatial differentiation of ecological risk.

As shown in Table 5, the mean ERI of the study area increased from 0.21 in 2000 to 0.26 in 2010 and further to 0.30 in 2020, representing an overall increase of approximately 42.86% over the two decades. This trend indicates a progressive deterioration of regional ecological security. The proportion of low-risk areas remained relatively stable throughout the study period, consistently accounting for approximately 65.00% of the total area. In contrast, the proportion of low-to-moderate-risk areas decreased from 34.31% in 2000 to 32.39% in 2020,

exhibiting a gradual contraction trend. Meanwhile, the proportion of moderate-risk areas increased from 0.91% to 1.71%, nearly doubling over the same period. More notably, the area classified as high risk expanded by approximately 166.00%, increasing from 0.35 km² to 0.93 km². Overall, the ecological risk pattern of the study area was characterized by the persistent dominance of low-risk areas, the gradual contraction of low-to-moderate-risk areas, and the continuous expansion of moderate- and high-risk areas. In particular, the rapid growth of high-risk zones indicates a localized intensification of ecological risk. Spatially, ecological risk evolution exhibited a distinct pattern of “rapid change in the south and relative stability in the north”, which closely corresponded to land-use transformation patterns (Figure 5). Both the rate and magnitude of risk escalation were substantially greater in the southern region than in the northern region, highlighting the influence of spatial heterogeneity in urbanization intensity on ecological risk dynamics.

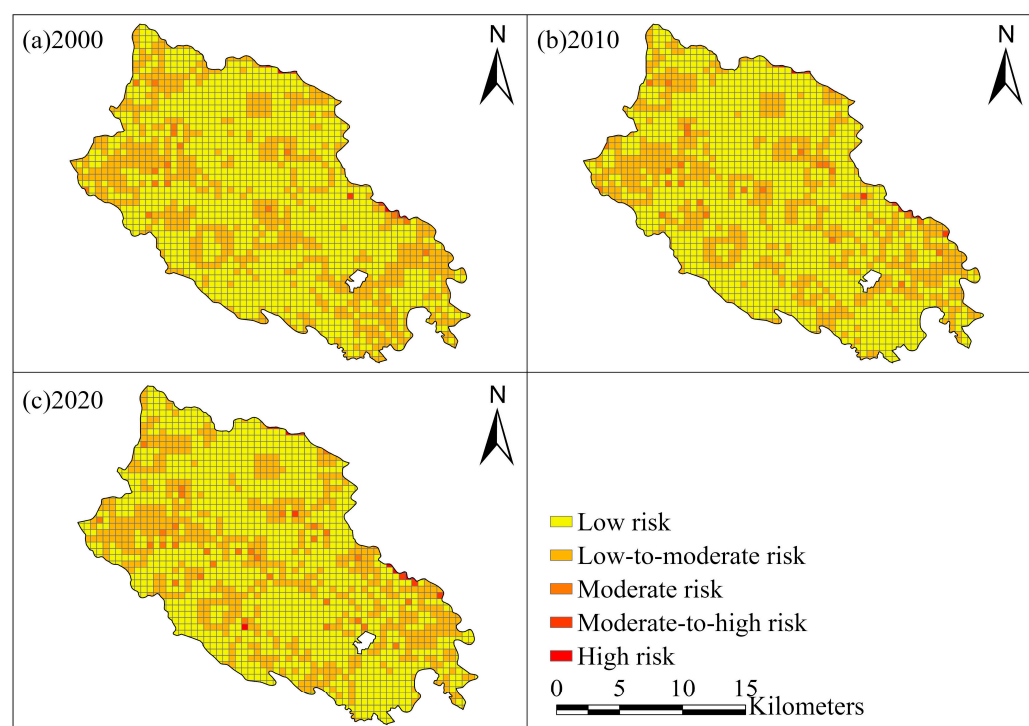


Figure 5. Spatial distribution pattern of ecological risk in Pidū District: (a) 2000; (b) 2010; (c) 2020.

Table 5. Areas and proportions of different ecological risk levels in Pidū District from 2000 to 2020 (unit: km²).

Ecological Risk Level	Area (Proportion)		
	2000	2010	2020
Low risk	279.54 (64.55%)	289.31 (66.80%)	283.3 (65.44%)
Low-to-moderate risk	148.61 (34.31%)	136.62 (31.54%)	140.22 (32.39%)
Moderate risk	3.96 (0.91%)	5.96 (1.38%)	7.41 (1.71%)
Moderate-to-high risk	0.63 (0.15%)	0.98 (0.23%)	1.05 (0.24%)
High risk	0.35 (0.08%)	0.23 (0.05%)	0.93 (0.22%)
Mean ERI	0.21	0.26	0.30

Table 6. Ecological risk level transition matrix from 2000 to 2010.

		2010				
		High Risk	Low Risk	Low-to-Moderate Risk	Moderate Risk	Moderate-to-High Risk
2000	High risk	0.23	0.00	0.00	0.00	0.12
	Low risk	0.00	232.10	46.19	1.25	0.00
	Low-to-moderate risk	0.00	56.96	90.15	1.25	0.24
	Moderate risk	0.00	0.25	0.25	3.46	0.00
	Moderate-to-high risk	0.00	0.00	0.00	0.00	0.63

Table 7. Ecological risk level transition matrix from 2010 to 2020.

		2020				
		High Risk	Low Risk	Low-to-Moderate Risk	Moderate Risk	Moderate-to-High Risk
2010	High risk	0.23	0.00	0.00	0.00	0.00
	Low risk	0.25	254.23	32.57	2.25	0.00
	Low-to-moderate risk	0.00	28.66	106.25	1.54	0.00
	Moderate risk	0.05	0.42	1.39	3.36	0.73
	Moderate-to-high risk	0.40	0.00	0.01	0.25	0.32

The ecological risk transition matrices (Tables 6 and 7) capture a dynamic, intensifying shift in risk levels across Pidū District over the two decades. During 2000–2010, the landscape was characterized by an upward risk drift in safer zones and bidirectional transitions in intermediate areas. Specifically, 16.50% of low-risk areas (46.19 km²) degraded to low-to-moderate risk, while low-to-moderate-risk areas showed noticeable fluctuations, with 56.96 km² reverting to low risk. Notably, high-risk zones exhibited strong persistence, suggesting that elevated ecological risk may be maintained under continued urbanization pressure and may require targeted management interventions for effective mitigation. During 2010–2020, risk transitions accelerated and grew more complex. Low-risk areas continued to degrade, with 0.25 km² directly escalating to the high-risk category. The deterioration of moderate-to-high-risk zones intensified significantly, with 41.10% (0.40 km²) further deteriorating into high-risk areas. This indicates accelerated ecological degradation at the fringes of high-risk zones, whereas core high-risk areas remained largely stable. The Sankey diagram (Figure 6) further demonstrates that ecological risk exhibited a predominantly unidirectional and cumulative transition from lower to higher risk levels during 2000–2020. Low-risk areas continuously shifted toward higher-risk categories, while moderate- and high-risk areas exhibited stronger persistence of elevated ecological risk levels, pointing to a continuous net increase in overall ecological risk.

In summary, these results indicate that ecological risk in the study area underwent a process characterized by both continuous growth and structural reorganization between 2000 and 2020. On the one hand, the steady increase in mean ERI and the continuous expansion of moderate- and high-risk areas suggest the ongoing accumulation of ecological security pressures. On the other hand, the transition process reveals clear stage-specific characteristics and a consistent upward trajectory, with low-risk areas progressively shifting toward higher risk categories and contributing to an overall increase in ecological risk. In particular, the growing occurrence of cross-level transitions after 2010 suggests that

ecological risk evolution shifted from a gradual process to a more accelerated trajectory. Spatially, the increasingly pronounced pattern of “rapid change in the south and relative stability in the north” further highlights the dominant role of urbanization gradients in shaping ecological risk dynamics and intensifying intra-regional spatial differentiation.

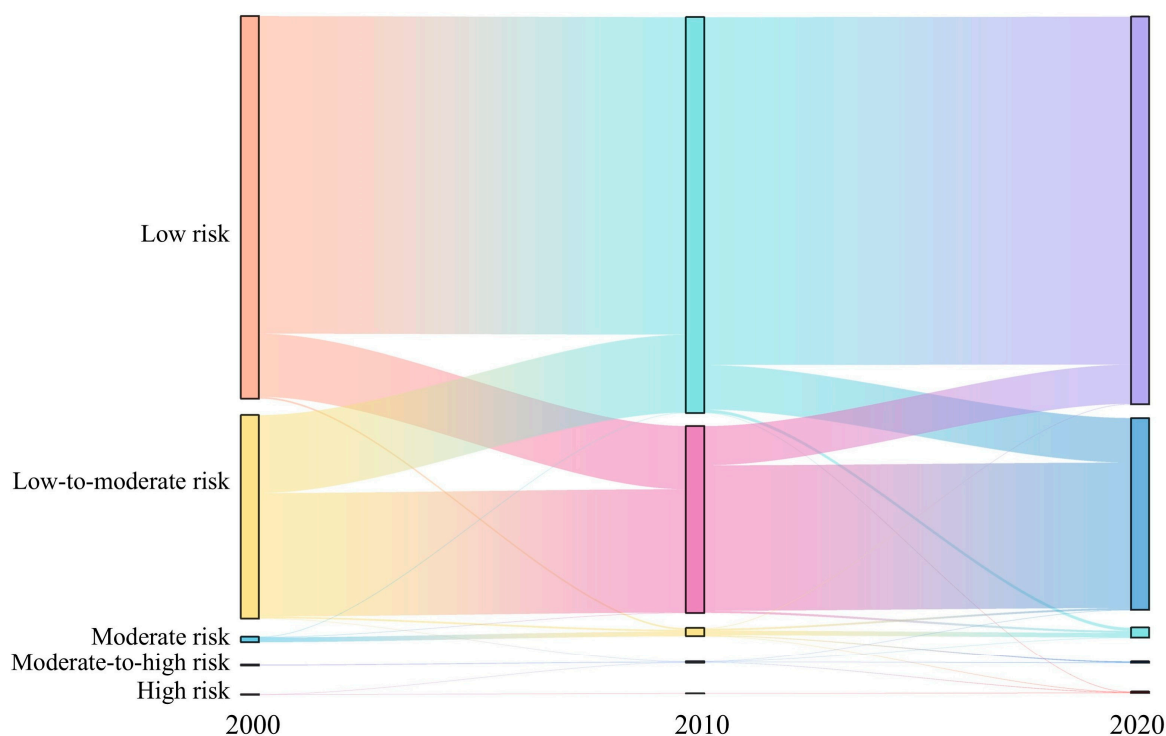


Figure 6. Ecological risk transitions from 2000 to 2020.

3.4. Assessment of Agroforestry Landscape Fragmentation

To reveal the structural evolution of agroforestry landscapes in Pidū District under rapid urbanization, this study conducted a comprehensive quantitative assessment and temporal comparison of agroforestry landscape fragmentation (CLFI) based on six landscape metrics, namely mean patch size (MPS), largest patch index (LPI), edge density (ED), area-weighted mean shape index (AWMSI), patch density (PD), and fragmentation index (FS) (Table 8, Figure 7).

In terms of patch size and shape characteristics, MPS remained extremely low and unchanged at 0.0001 throughout 2000–2020, indicating that agroforestry landscape patches persisted at a very small spatial scale and exhibited no evidence of size recovery over time. This finding suggests the long-term persistence of a highly fragmented landscape structure. Similarly, LPI remained constant at 0.0001, reflecting the absence of dominant agroforestry patches and a highly fragmented and homogeneous landscape pattern. AWMSI remained stable at 1.00 throughout the study period, indicating that patch shapes were generally regular and strongly influenced by agricultural management and land consolidation, with little evidence of increasing shape complexity.

Regarding fragmentation intensity, ED exhibited a continuous upward trend, increasing from 0.42 in 2000 to 0.54 in 2020, representing an increase of approximately 29.0% over the study period. This trend suggests a progressive increase in patch boundary complexity and a continual intensification of landscape subdivision. Changes in PD were even more pronounced, rising from 0.001 in 2000 to 0.02 in 2020—an increase of more than tenfold. This substantial increase indicates that agroforestry landscapes underwent considerable patch restructuring and accelerated spatial subdivision, particularly during the later stage

of urbanization. Consistent with these trends, FS remained at its maximum value of 1.00 throughout the study period, indicating that agroforestry landscapes persistently remained in a highly fragmented state.

Overall, CLFI increased from 0.46 in 2000 to 0.48 in 2020, representing an overall increase of approximately 4.80%. This result indicates a continued intensification of agroforestry landscape fragmentation during the study period. The increasing fragmentation was accompanied by intensified landscape subdivision and changes in structural characteristics, which may partially explain the spatial coincidence between agroforestry landscape fragmentation and the observed increase in ecological risk.

Table 8. Standardized fragmentation indicators of agroforestry landscapes in Pidū District from 2000 to 2020.

Landscape Indicator	2000	2010	2020
MPS	0.0001	0.0001	0.0001
LPI	0.0001	0.0001	0.0001
ED	0.42	0.43	0.54
AWMSI	1.00	1.00	1.00
PD	0.001	0.002	0.02
FS	1.00	1.00	1.00
CLFI	0.46	0.46	0.48

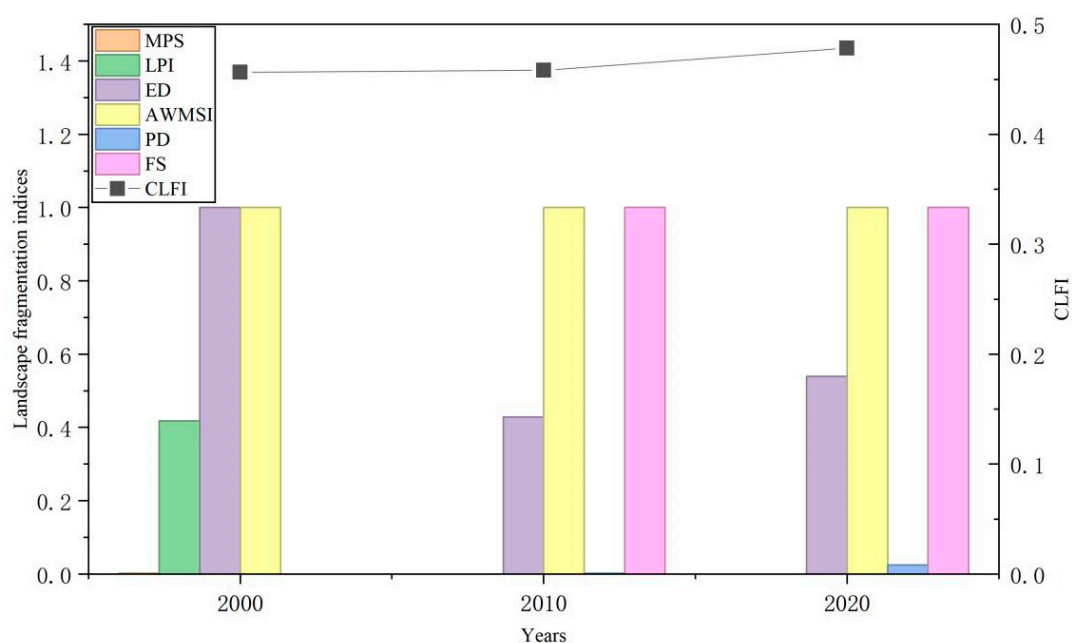


Figure 7. Temporal changes in agroforestry landscape fragmentation indicators from 2000 to 2020.

4. Discussion

4.1. Evolution Characteristics of Agroforestry Landscape Patterns Under Changing Urban Development Contexts

From 2000 to 2020, the area of agroforestry landscapes in Pidū District decreased by 24.53%, exhibiting a phased pattern characterized by a rapid decline during 2000–2010 and a slower rate of reduction during 2010–2020. This trajectory occurred during a period of adjustments in Chengdu’s urban spatial development strategy. During 2000–2010, Chengdu experienced a monocentric expansion phase, accompanied by strong outward diffusion of urban functions from the city center. Given its proximity to the urban core,

southern Pidū District became a major frontier of urban expansion, where extensive agroforestry landscapes were converted into construction land. After 2010, urban development patterns changed in the context of the polycentric development strategy and the West Control Policy [30,31], with urban growth increasingly concentrated in the eastern and southern parts of Chengdu. Meanwhile, Pidū District was increasingly recognized as an important ecological buffer in western Chengdu, corresponding to a marked slowdown in construction land expansion. These stage-specific changes suggest that spatial planning and land-use regulation may have contributed to landscape dynamics in peri-urban areas. Consequently, the conservation of agroforestry landscapes appears to be related to the strategic orientation of higher-level territorial spatial planning.

It is noteworthy that the shrinkage of agroforestry landscapes was not solely associated with conversion to construction land. Instead, persistent bidirectional transitions occurred between cropland and agroforestry landscapes throughout the study period. During 2000–2010, approximately 25.17 km² of agroforestry landscapes were converted to cropland, while 23.01 km² of cropland transitioned into agroforestry landscapes, indicating a relatively balanced exchange. Although the scale of these transitions declined slightly during 2010–2020, the overall bidirectional pattern remained evident. This phenomenon reflects the dynamic nature of land-use systems in peri-urban areas. On the one hand, agroforestry landscapes may be simplified into cropland under intensified agricultural production. On the other hand, marginal cropland may gradually evolve into agroforestry landscapes through farmland abandonment, ecological restoration, or vegetation recovery. While these bidirectional transitions partially offset the net loss of agroforestry landscapes, they also indicate persistent instability in landscape boundaries and spatial configurations, which may challenge the long-term maintenance of ecological functionality. From the perspective of ecosystem services, frequent land-use transitions may disrupt the continuity of ecological processes and weaken the stable provision of regulating services, particularly biodiversity conservation and water retention [32]. These findings highlight the importance of not only conserving the area of agroforestry landscapes but also maintaining their spatial stability and functional integrity through targeted land-use management and ecological conservation strategies.

4.2. Ecological Risk Characteristics and Their Relationship with Landscape Fragmentation

Ecological risk in Pidū District exhibits a pronounced spatial pattern characterized by higher values in the south and lower values in the north. This spatial gradient reflects the combined influence of urbanization intensity and changes in agroforestry landscape structure.

The concentration of high ecological risk in the southern region can be largely coincided with the synergistic effects of urban expansion and landscape fragmentation. On the one hand, the rapid expansion of construction land has continuously encroached upon agroforestry landscapes, gradually transforming the regional landscape matrix from agricultural and ecological land into urbanized land. On the other hand, the increasingly dense transportation network, including the Ring Expressway, the Chengdu–Dujiangyan Expressway, and rail transit infrastructure, has further fragmented the remaining agroforestry patches, a process that was accompanied by higher edge density and greater patch isolation. The results show that areas experiencing rapid increases in the ERI largely coincide with areas characterized by substantial increases in edge density (ED) and patch density (PD), suggesting that landscape fragmentation is closely associated with ecological risk escalation. This finding is consistent with previous studies demonstrating that urban expansion and the fragmentation of agricultural and natural landscapes tend to correspond with elevated

landscape ecological risk. It also supports the applicability of landscape pattern-based ecological risk assessment models in peri-urban regions [27,33].

In contrast, the northern region has maintained a relatively low ecological risk throughout the study period, primarily linked to the preservation of an intact agroforestry landscape mosaic. This area retains the characteristic Linpan landscape of the western Sichuan Plain, in which cropland, forestland, and water bodies collectively form a highly connected ecological network. The relatively low intensity of urban development has further enabled agroforestry patches to retain a more intact spatial configuration. These findings indicate that traditional agroforestry landscapes function not only as important production spaces [34] but also as critical ecological foundations for maintaining regional ecological security [35]. Their relatively high structural integrity may contribute to ecological stability under rapid urbanization pressure [36].

4.3. Comparison with Previous Studies

A comparison with previous studies conducted in similar peri-urban regions reveals that the evolution of agroforestry landscapes in Pidū District exhibits both common patterns and distinctive regional characteristics.

In terms of commonalities, the landscape dynamics observed in Pidū District closely resemble those reported for peri-urban areas in northern Italy by Smiraglia et al. [10]. In both cases, urban expansion primarily encroached upon agroforestry landscapes located near urban cores, a pattern that corresponded to a spatial gradient of landscape degradation from urban to rural areas. Transportation infrastructure acted as a major factor linked to landscape fragmentation, while agroforestry landscapes experienced a more rapid decline than individual cropland patches. This suggests that the responses of agroforestry landscapes in peri-urban areas to urbanization follow broadly consistent patterns across different geographical contexts, while also providing external validation for the methodological framework and interpretation of the results presented in this study.

Despite these common trends, Pidū District also displays several distinctive regional characteristics. First, the scale of bidirectional transitions between cropland and agroforestry landscapes is substantially greater than that reported in comparable studies. This pattern is closely related to the long-established agricultural traditions and high multiple-cropping intensity of the Chengdu Plain, which promote continuous adjustments in the spatial configuration of cropland and agroforestry landscapes. Second, agroforestry-balanced landscapes exhibited a continuous expansion during the study period, increasing from 22.24 km² to 30.55 km². This trend contrasts with findings from many other peri-urban regions and reflects the strong cultural resilience and ecological value of the Linpan landscape, a distinctive traditional landscape of the western Sichuan Plain. Under the combined influence of the policy and dedicated Linpan conservation programs, these agroforestry landscape mosaics have been effectively preserved and, in some areas, further expanded.

4.4. Policy Implications for Agroforestry Spatial Governance in Peri-Urban Areas

As a typical peri-urban district within the Chengdu metropolitan area, Pidū District provides valuable insights into the spatial governance of agroforestry landscapes in similar peri-urban regions. Based on the observed spatiotemporal evolution of landscape fragmentation and ecological risk, the following implications can be drawn.

(1) Ecological risk management in peri-urban agroforestry landscapes should shift from an area-oriented approach to a structure-oriented early-warning framework. Although the area of agroforestry landscapes in Pidū District continued to decline between 2000 and 2020, the rate of reduction slowed during the later period. However, this slowdown in area loss was not accompanied by an improvement in landscape structure. Metrics

such as MPS, LPI, and AWMSI remained persistently low, while FS remained close to saturation and both PD and ED increased significantly. These findings indicate that structural degradation continued despite the deceleration of area loss. Therefore, relying solely on land-area monitoring may underestimate the actual decline in ecological functions. It is necessary to incorporate structural indicators into ecological monitoring systems and establish a multidimensional early-warning framework integrating area, structure, and function, thereby enabling the timely detection of hidden ecological degradation.

(2) Conservation strategies for agroforestry landscapes should place greater emphasis on structural optimization. The long-term stability of patch size, dominance, and shape complexity at relatively low levels suggests limited structural resilience within the agroforestry landscape system. Under such conditions, the expansion of construction land and the proliferation of transportation infrastructure are more likely to translate directly into increased fragmentation. In high-risk areas of southern Pidu District, management efforts should focus on reducing new sources of landscape dissection, optimizing transportation corridors, and establishing ecological buffer zones to minimize further fragmentation of remaining agroforestry patches. In contrast, low-risk areas in the north should prioritize the preservation of integrated agroforestry landscape mosaics, particularly the traditional Linpan system. Delineating stable ecological conservation units and maintaining clear ecological boundaries may help support structural stability [37].

(3) Spatial governance strategies should account for the dynamic nature of urban development. The study reveals a clear shift in the rate of agroforestry landscape loss around 2010, which closely corresponds to adjustments in Chengdu's urban development strategy. This finding highlights that peri-urban ecological spaces are dynamic systems whose evolution is strongly influenced by different stages of urban expansion. Consequently, governance strategies should be adapted to changing development contexts. During periods of rapid urban growth, priority should be given to protecting core agroforestry patches with high ecological value and relatively intact structures. As urban expansion slows, management efforts can gradually shift toward optimizing the structure of already fragmented landscapes, thereby strengthening the stability of the broader ecological network.

(4) Greater attention should be paid to the structural adjustment potential reflected by bidirectional transitions between cropland and agroforestry landscapes. The results demonstrate a persistent and relatively balanced pattern of bidirectional conversion between these two landscape types throughout the study period. This suggests that peri-urban land-use systems are not characterized by uniform trajectories of change and may retain certain capacity for structural adjustment under appropriate management interventions. For example, marginal cropland may gradually develop into agroforestry landscapes through ecological restoration or low-intensity land use, whereas some agroforestry landscapes may be converted into cropland under agricultural intensification. Such dynamic transitions provide opportunities for ecological space optimization but also require appropriate temporal regulation and spatial guidance to avoid disorderly land-use changes that could further destabilize landscape structure.

Overall, the case of Pidu District demonstrates that ecological spatial governance in peri-urban areas should move beyond the extensive management of land area alone and place greater emphasis on landscape structural integrity. Developing a structure-oriented governance framework that is spatially differentiated and dynamically adaptive would strengthen both the effectiveness and the forward-looking capacity of ecological risk management.

4.5. Future Research Directions

The landscape ecological risk assessment framework developed in this study is based on two dimensions—landscape disturbance and landscape vulnerability—which effectively capture ecological risks associated with changes in landscape patterns. However, several non-landscape factors that may substantially influence ecological security, including climate change (e.g., increasing frequency of extreme precipitation events), soil degradation (e.g., declines in soil organic matter), and water pollution (e.g., agricultural non-point source pollution), were not incorporated into the assessment framework. Future studies could establish a more comprehensive indicator system integrating landscape pattern risk, environmental quality risk, and climate-related risk. Approaches such as composite index methods or Bayesian network models may be employed to provide a more holistic evaluation of ecological security in peri-urban areas.

In addition, this study primarily focused on landscape pattern dynamics and ecological risk assessment, while the underlying socioeconomic driving mechanisms were not explicitly examined. Future research could incorporate spatial econometric approaches, such as spatial lag models and spatial error models, as well as geographically weighted regression, to quantitatively assess the effects of road density, population distribution, economic development, and other socioeconomic factors on agroforestry landscape fragmentation and ecological risk. Furthermore, integrating social surveys and analyses of farmers' land-use behavior would help reveal how individual land-use decisions influence the evolution of agroforestry landscape patterns from a human–environment interaction perspective. Such efforts would complement remote sensing-based analyses and contribute to a more comprehensive understanding of the mechanisms underlying landscape transformation and ecological risk evolution in peri-urban regions.

5. Conclusions

Using land-use data from 2000, 2010, and 2020, this study investigated the evolution of agroforestry landscapes, ecological risk, and landscape fragmentation in Pidu District, Chengdu, China, under rapid urbanization.

The results show that cropland-dominated agroforestry landscapes were the dominant landscape type throughout the study period. From 2000 to 2020, the area of agroforestry landscapes decreased continuously, a decline primarily tied to the expansion of construction land, although relatively stable bidirectional transitions between cropland and agroforestry landscapes persisted. Ecological risk increased steadily over time, with moderate-to-high and high-risk areas concentrated in the rapidly urbanizing southern region, while low-risk areas remained primarily distributed in the traditional agricultural landscapes of the north. Meanwhile, agroforestry landscape fragmentation intensified, as reflected by increasing edge density and patch density, indicating increased fragmentation and more complex patch boundaries. Furthermore, the spatial pattern of ecological risk was closely associated with agroforestry landscape fragmentation, highlighting the potential relationship between landscape structural degradation and ecological risk variation in peri-urban areas.

Overall, this study reveals the coupled evolution of agroforestry landscape loss, fragmentation, and ecological risk under rapid urbanization and provides scientific support for agroforestry landscape conservation, ecological risk management, and territorial spatial optimization in similar peri-urban regions.

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vision, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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