Landscape Ecological Risk Assessment for the Tarim River Basin on the Basis of Land-Use Change

Guangyao Wang 1,2,3, Guangyan Ran 2, Yaning Chen 1,* and Zhengyong Zhang 2

Abstract: Land-use variation indicates the spatial differentiation of regional ecological risk. Landscape ecological risk assessment (LERA) has been used for the measurement and prediction of environmental quality. In the present study, the land-use dynamics of the Tarim River Basin from 2000 to 2020 were quantitatively analyzed using ENVI 5.6 software based on Landsat TM and ETM+ images (2000, 2010, and 2020). Moreover, the ecological risk level and its spatiotemporal differentiation features were explored using geostatistical methods based on landscape pattern indices. The results show that: (1) From 2000 to 2020, the arable land area increased the most (12,130.272 km²), and the woodland, wetland, water bodies, and building-land areas increased by 2416.541 km², 4103.789 km², 3331.230 km², and 2330.860 km², respectively. However, the bare-land area decreased the most (18,933.943 km²). (2) From 2000 to 2020, a decrease was detected in the landscape ecological risk index (LERI) of the basin, and the very low-, low-, and moderate-risk areas had the largest decrease. In addition, the area of the low- and moderate-risk areas gradually increased, while that of the high-risk areas was reduced. (3) The conversion rate of low-risk areas to very low-risk areas was the largest (5144.0907 km²/a), followed by that of high-risk areas to moderate-risk areas (4994.4765 km²/a). Therefore, the overall landscape ecological risk (LER) of the basin was reduced from 2000 to 2020, but the ecological risk of some areas, especially that of the glaciers and permanent snow-covered areas, still needs close attention.

Keywords: land cover; landscape pattern; ecological safety; spatial analysis

1. Introduction

Land-use change (LUC), denoting changes in land cover caused by human activities, further results in changes to the environment [1]. Improper land use and high development intensity not only affect the elements of the environment, but also cause changes in the regional landscape structure and ecosystem, which may bring ecological risks and threaten regional ecological security [2,3]. Therefore, many scholars have analyzed the characteristics and causes of LUC [4,5], and have established global and regional models based on LUC, aiming to reveal the key drivers and predict future trends [2].

The LER denotes the adverse influence of natural and social–economic interference on the natural environment, including landscape constituents, frameworks, and functions. LERA uses landscape types to measure the evolution of land use, potential risks, and risk distribution, which can clarify the features of the dynamics of regional ecological risks [6–9]. In the context of environment assessment, LERA focuses on the scientific judgment of the environment risk threshold and proposes risk-management measures [8]. Currently, some scholars measure the LER from the cross-integration of landscape heterogeneity and landscape correlation, and pay attention to the risk from spatiotemporal heterogeneity [10,11].

LERA can quantitatively assess the ecological effects of land-cover change. Thus, it can provide references for regional risk management. LERA has gone through more
than 40 years of development. The assessment content has gradually evolved from the initial single-factor and single-risk evaluation/multi-factor and single-risk evaluation to multi-factor and multi-risk evaluation [7]. In addition to chemical pollution [12] and soil pollution [13,14], the impact of environmental and ecological events on the natural environment has also been a focus [15]. The research scale extends from microscopic, single populations, to the urban [15], regional [16], watershed [17], ocean [18], ecosystem [19], and other medium and macro scales [16]. In terms of assessment methods, the LERI, on the basis of landscape pattern indices, has been applied to LERA [7]. For example, Li et al. [20] constructed an analysis framework composed of potential, connectivity, and resilience, based on an adaptive cycle to measure the spatial heterogeneity and drivers of LER, and found that human factors were the major drivers of LER. Wu et al. [21] proposed an LERA method based on the source–sink theory, and found that the source–sink theory could be used to accurately distinguish the ecological risks of mining areas. In addition, Paul et al. [22] proposed a LERA method based on ecological conservation objectives, ecological scenarios, interactions between species, potential sources, the interactions of stresses, and causal models. This method can apply emerging tools, such as big data and ecological modeling. It can be seen that great progress has been made in the study of LERA at home and abroad. However, the research areas are mainly concentrated on lakes, rivers, and estuarine deltas [14] in humid areas, semi-humid areas, and arid areas, and there are few reports on LERA for the Tarim River Basin. Therefore, this study performed a LERA for the Tarim River Basin, which has a great significance for the sustainable development of the basin.

Located in Central Asia, the Tarim River originates in the Kunlun Mountains and Tianshan Mountains and finally flows into Terma Lake. The Tarim River Basin is a cotton production base and a petrochemical base in China [22,23]. However, there are many problems in the basin, such as water shortages and a low ecological carrying capacity. Due to the impacts of human activities, climate warming, etc., the integrity of the water system in the basin is broken. The Chechen, Dina, and Kriya rivers lost their connection to the main stream of the Tarim River in the 1940s, causing great damage to the ecosystem [24]. Therefore, since 2000, the government has implemented a comprehensive ecological restoration project.

Under an extremely fragile environment and the influence of natural factors, it is not clear how effective this comprehensive ecological restoration project has been, how land use in the basin has changed, and whether the fragile environment has been improved. In particular, systematic research is still lacking. This study hypothesized that land use changed greatly from 2000 to 2020, and the fragile environment was improved under the comprehensive ecological restoration project. To verify this hypothesis, based on Landsat TM and ETM+ images (2000, 2010, and 2020), this study conducted a LERA to assess the vulnerability of the basin to human interventions and natural factors, and the mechanism of LUC was also explored. In addition, the spatial-variation features of LER and the relationship between LER and LUC were analyzed on the basis of the LERI.

2. Materials and Methods

2.1. Study Site

The Tarim River Basin (about 1.028 × 106 km²) is located in northwest China (71°39′–93°45′E, 34°20′–43°39′N). The basin is connected to the Tianshan Mountains in the north, the Kunlun Mountains in the south, and the Pamir Plateau in the west. The Taklamakan Desert, China’s largest desert, is located in the center of the basin. Mountains, oases, and deserts are the most abundant components of the basin. The rivers originate in the mountains [24]. The Tarim River has a total length of 2179 km, and the main water source is glacial meltwaters [24–26]. The annual mean temperature is 10.6–11.5 °C and the annual mean precipitation is 17.4–42.8 mm [25]. Bare land and grassland are the dominant landscapes.
2.2. Data Processing

The Landsat TM/ETM+ image data from 2000, 2010, and 2020 (June–October, cloud cover < 10%) were collected from https://www.resdc.cn/ (accessed on 8 January 2023). Then, ENVI was employed to preprocess the data by stitching, cropping, etc. After that, land use was categorized into nine types, including forest land, grassland, shrubland, water body, farmland, building land, and bare land. In addition, the categorization accuracy was verified using the Kappa coefficient [25]. It was found that the Kappa coefficients were all above 0.85, indicating a high categorization accuracy.

2.3. Methods

2.3.1. Division

To accurately display the spatial variation in the LERI, considering the workload of sampling and calculation, the basin was divided into 1293 LERA grids (33 × 33 km) [27,28], based on the criterion of 2–5 folds of the mean area of the different landscape patches (Figure 1). The LER model (see Section 2.3.2) was used to calculate the LERI for the central point of each grid, followed by a spatial interpolation analysis [27,28].

![Figure 1. Overview of the Tarim River Basin and division of ecological risk-assessment grids.](image-url)

2.3.2. Establishment of LER Model

The environmental vulnerability of the basin is manifested by regional desertification and an irreversibly damaged ecological balance [29]. The basin has an arid ecosystem, including oases, mountains, and deserts, among which the oases are always in a changing state due to the impacts of frequent social and economic activities, which form complex landscape structures with the highest diversity of all the landscapes [9]. Therefore, in
combination with landscape ecology methods, the $U_i$ (landscape disturbance index), $E_i$ (landscape vulnerability index), and $R_i$ (landscape loss index) were used to construct a LERA model, and the ERI [29–31] for each grid was calculated (Table 1). The ERI was constructed according to the area proportions of the land-use types and the $R_i$. The ERI describes the degree of comprehensive loss of the environment in each grid. The higher the value, the higher the degree of ecological risk. The ERI can quantitatively describe the ecological risk for each grid, and clarify the relevance of landscape structures and ecological risk. Therefore, it can characterize landscape pattern changes and spatial variation in the LER. The $U_i$ reflects the degree and frequency of different types of external disturbances in a certain area. In this study, the $C_i$ (landscape fragmentation index), $S_i$ (landscape separation index), and $K_i$ (landscape dominance index) were employed to calculate the $U_i$ by superimposing certain weights (Table 1) (the weights of each parameter were determined on the basis of previous research results [29–31]). For the LERA, $E_i$ is the most important indicator, because $E_i$ indicates the sensitivity of a landscape type to disturbance factors.

Table 1. Landscape pattern indices and calculation methods.

<table>
<thead>
<tr>
<th>Landscape Pattern Indices</th>
<th>Formula</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landscape fragmentation index ($C_i$)</td>
<td>$C_i = \frac{n_i}{A_i}$, where $n_i$ is the patch number of landscape $i$, and $A_i$ is the total area of landscape $i$.</td>
<td>It indicates the degree of landscape fragmentation, the landscape’s spatial structure, and the degree of interference with the landscape.</td>
</tr>
<tr>
<td>Landscape separation index ($S_i$)</td>
<td>$S_i = \Delta A_i \sqrt{\frac{n_i}{A_i}}$, where $A$ is the total area of landscape type $i$.</td>
<td>It indicates the separation degree of patches of a landscape type.</td>
</tr>
<tr>
<td>Landscape dominance index ($K_i$)</td>
<td>$K_i = \frac{1}{4} \left( \frac{n_i}{N} + \frac{m_i}{M} \right) + \frac{A_i}{A}$, where $n_i$ is the number of grids that appear in patches of landscape $i$, $M$ is the total number of grids, and $N$ is the total number of patches of landscape type $i$.</td>
<td>The dominance of a landscape type is negatively correlated to the diversity index. For landscape types with the same number, the greater the diversity index, the smaller the dominance.</td>
</tr>
<tr>
<td>Landscape disturbance index ($U_i$)</td>
<td>$U_i = aC_i + bS_i + cK_i$, where $a$, $b$, and $c$ represent weights ($a + b + c = 1$, $a = 0.5$, $b = 0.3$, $c = 0.2$).</td>
<td>The vulnerability index of each landscape type can be obtained after normalization. It indicates the ability of different landscape types to resist interference and their sensitivity to external changes. The smaller the ability to resist external interference, the greater the vulnerability, and the greater the ecological risk.</td>
</tr>
<tr>
<td>Landscape loss index ($R_i$)</td>
<td>$R_i = U_i \times E_i$</td>
<td>It indicates the loss of each landscape type under disturbance. It is a synthesis of the disturbance index and vulnerability index.</td>
</tr>
<tr>
<td>Landscape ecological risk index (ERI)</td>
<td>$ERI_i = \sum_{i=1}^{N} \frac{A_{i_k}}{N} R_i$, where $N$ represents the number of landscape types, $A_{i_k}$ represents the area of landscape type $i$ in the $k_{th}$ grid, and $A_k$ is the area of the $K_{th}$ grid.</td>
<td>The $ERI$ was constructed according to the area proportions of land-use types and the $R_i$. The $ERI$ describes the degree of comprehensive loss of the environment in each grid. The higher the value, the higher the degree of ecological risk.</td>
</tr>
</tbody>
</table>

To reveal the spatial features of the areas with different levels of LER in the basin, based on each grid’s ERI value, the distribution of the different LER levels was obtained using the ordinary kriging interpolation function. According to the distribution of ERI values for the three years, Jenks in ArcGIS [32] was used to classify the ERI values into...
five classes [29–31,33], including very low risk (0.036–0.047), low risk (0.047–0.052), moderate risk (0.052–0.057), high risk (0.057–0.065), and very high risk (0.065–0.114). In addition, for each risk level of the landscape, the proportion and area were calculated [29].

2.3.3. Spatial Analysis Methods

LERA focuses on spatiotemporal variation and the scale effect of risk. It comprehensively characterizes the risks from multiple sources and visualizes the spatial distribution of the risks. To clearly describe the spatial variation in LER, geostatistics [34] based on GIS 10.2 software were used to spatially map the LER by summation, sampling, and ordinary kriging spatial interpolation. In addition, the spatial features, conversion, and area of each LER level from 2000 to 2020 were quantitatively measured, and the reasons for conversions were also analyzed.

3. Results

3.1. Analysis of LUC

From 2000 to 2020, the area of arable land grew the most. In addition, building land increased at the highest rate (Figures 2 and 3). The area of arable land, woodland, and shrubland increased by 12,130 (31.84%), 2417 (118.56%), and 43.32 (0.82%) km$^2$, respectively. Moreover, the area of wetland, water bodies, and building land increased by 4104 (126.00%), 3331 (65.17%), and 2331 (237.84%) km$^2$, respectively.

![Figure 2. Area proportion of each landscape type in the study area.](image-url)
drastically from 2000 to 2020. According to the area conversion and number of landscape patches, C_i, S_i, and R_i (Table 2), it was found that the landscape pattern evolved significantly. This indicates that the area of water bodies and the connection between water systems increased. The K_i of arable land and building land increased, but the S_i, U_i, and R_i

The land-use type conversion matrix from 2000 to 2020 was obtained by the superposition of the classified images of two adjacent time points using ArcGIS 10.2 software. The grassland, bare land, and glaciers and permanent snow cover were mainly converted into arable land, woodland, wetland, water bodies, and building land. Among them, the area of new arable land was the largest (12,083.88 km²), and was mainly converted from grassland (4780 km²) and bare land (8519.32 km²). The grassland area reduced the most, and was mainly converted into bare land (2285.54 km²) and arable land (4780.38 km²). From 2000 to 2020, the area of arable land and grassland changed the most, and there were also varying degrees of conversion between the other land-use types (Figure 3).

3.2. Analysis of Spatiotemporal Changes of LER

3.2.1. Temporal Change of Landscape Pattern Indices

From 2000 to 2020, the ERI value of the basin reduced from 0.134 to 0.119, and the minimum and average ERI values in 2020, 2010, and 2020 were reduced. That is, the overall LER decreased from 2000 to 2020. According to the area conversion and number of landscape patches, C_i, S_i, and R_i (Table 2), it was found that the landscape pattern evolved drastically from 2000 to 2020.

From 2000 to 2020, the patch number of arable land and building land in the basin continuously grew, while that of the grassland, bare land, glaciers and permanent snow cover decreased (Table 2). In addition, the patch number of the other landscape types first increased and then decreased. It should be noted that the patch number of building land increased the most, from 3346 in 2000 to 10,201 in 2020 (more than 2.0 times), and the area of the building land also increased (Table 2). This indicates that with the acceleration of urbanization [35], the landscape types are very disturbed by human beings, the landscape fragmentation degree increases, and the stability of the landscape structure declines. For the other indices, the water-body area significantly increased but its C_i was reduced significantly. This indicates that the area of water bodies and the connection between water systems increased. The K_i of arable land and building land increased, but the S_i, U_i, and R_i

Figure 3. Land-use changes in the Tarim River Basin from 2000 to 2020.

The land-use type conversion matrix from 2000 to 2020 was obtained by the superposition of the classified images of two adjacent time points using ArcGIS 10.2 software. The grassland, bare land, and glaciers and permanent snow cover were mainly converted into arable land, woodland, wetland, water bodies, and building land. Among them, the area of new arable land was the largest (12,083.88 km²), and was mainly converted from grassland (4780 km²) and bare land (8519.32 km²). The grassland area reduced the most, and was mainly converted into bare land (2285.54 km²) and arable land (4780.38 km²). From 2000 to 2020, the area of arable land and grassland changed the most, and there were also varying degrees of conversion between the other land-use types (Figure 3).

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were reduced. This may be due to the rapid increase in the patch number and the area of arable land and building land [36], reflecting the rapid increase in human activities in the basin. The Ki of woodland and wetland showed an increasing trend, and that of grassland increased slightly after decreasing. Other indices for the woodland, wetland, and grassland areas were reduced. This may be due to the fact that the 20-year ecological restoration project has played a positive role, and has reduced the disturbances to the woodland, wetland, and grassland areas. It is important to note that the number and area of glaciers and permanent snow-cover patches decreased obviously from 2000 to 2020, and the other indices showed an insignificant decreasing trend. The melting of the glaciers has a great impact on the regional ecosystem stability [37], which requires continuous attention.

Table 2. Landscape pattern indices for the Tarim River Basin from 2000 to 2020.

<table>
<thead>
<tr>
<th>Landscape</th>
<th>Time</th>
<th>Patch Number</th>
<th>Area (km²)</th>
<th>Fragmentation Index (C_i)</th>
<th>Separation Index (S_i)</th>
<th>Dominance Index (K_i)</th>
<th>Disturbance Index (U_i)</th>
<th>Vulnerability Index (E_i)</th>
<th>Loss Index (R_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arable land</td>
<td>2000</td>
<td>7225</td>
<td>38,099.66</td>
<td>0.1896</td>
<td>1.1451</td>
<td>0.0876</td>
<td>0.4559</td>
<td>0.1111</td>
<td>0.0507</td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>8052</td>
<td>41,676.19</td>
<td>0.1932</td>
<td>1.1051</td>
<td>0.0959</td>
<td>0.4473</td>
<td>0.1111</td>
<td>0.0497</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>9324</td>
<td>50,229.94</td>
<td>0.1856</td>
<td>0.9867</td>
<td>0.1060</td>
<td>0.4100</td>
<td>0.1111</td>
<td>0.0456</td>
</tr>
<tr>
<td>Woodland</td>
<td>2000</td>
<td>18,851</td>
<td>2038.16</td>
<td>9.2490</td>
<td>34.5767</td>
<td>0.0324</td>
<td>15.0040</td>
<td>0.0444</td>
<td>0.6668</td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>22,362</td>
<td>4043.25</td>
<td>5.3507</td>
<td>18.9387</td>
<td>0.0412</td>
<td>8.4687</td>
<td>0.0444</td>
<td>0.3764</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>20,434</td>
<td>4454.70</td>
<td>4.5871</td>
<td>16.4707</td>
<td>0.0449</td>
<td>7.2437</td>
<td>0.0444</td>
<td>0.3219</td>
</tr>
<tr>
<td>Grassland</td>
<td>2000</td>
<td>466,111</td>
<td>200,277.44</td>
<td>2.3298</td>
<td>37.9077</td>
<td>0.1756</td>
<td>29.3811</td>
<td>0.1333</td>
<td>0.2364</td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>377,141</td>
<td>192,878.51</td>
<td>1.9553</td>
<td>1.6343</td>
<td>0.3899</td>
<td>1.5459</td>
<td>0.1333</td>
<td>0.2061</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>312,003</td>
<td>199,639.40</td>
<td>1.5628</td>
<td>1.4361</td>
<td>0.3963</td>
<td>1.2915</td>
<td>0.1333</td>
<td>0.1722</td>
</tr>
<tr>
<td>Shrubland</td>
<td>2000</td>
<td>170,162</td>
<td>5297.92</td>
<td>32.1186</td>
<td>39.9651</td>
<td>0.1327</td>
<td>28.0754</td>
<td>0.1556</td>
<td>4.3673</td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>236,913</td>
<td>6590.57</td>
<td>35.9473</td>
<td>37.9077</td>
<td>0.1756</td>
<td>29.3811</td>
<td>0.1556</td>
<td>4.5704</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>191,282</td>
<td>5341.24</td>
<td>35.8123</td>
<td>42.0291</td>
<td>0.1695</td>
<td>30.5488</td>
<td>0.1556</td>
<td>4.7520</td>
</tr>
<tr>
<td>Wetland</td>
<td>2000</td>
<td>4265</td>
<td>3256.92</td>
<td>1.3095</td>
<td>10.2922</td>
<td>0.0491</td>
<td>3.7522</td>
<td>0.0889</td>
<td>0.3335</td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>3869</td>
<td>3565.53</td>
<td>1.0851</td>
<td>8.9543</td>
<td>0.0501</td>
<td>3.2389</td>
<td>0.0889</td>
<td>0.2879</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>7922</td>
<td>7360.71</td>
<td>1.0763</td>
<td>6.2066</td>
<td>0.0664</td>
<td>2.4134</td>
<td>0.0889</td>
<td>0.2145</td>
</tr>
<tr>
<td>Water body</td>
<td>2000</td>
<td>46,478</td>
<td>5111.62</td>
<td>9.0926</td>
<td>21.6481</td>
<td>0.1493</td>
<td>11.0706</td>
<td>0.0667</td>
<td>0.7380</td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>47,514</td>
<td>6494.06</td>
<td>7.3165</td>
<td>17.2286</td>
<td>0.1490</td>
<td>8.8566</td>
<td>0.0667</td>
<td>0.5904</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>33,386</td>
<td>8442.85</td>
<td>3.9544</td>
<td>11.1083</td>
<td>0.1439</td>
<td>5.3385</td>
<td>0.0667</td>
<td>0.3559</td>
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<tr>
<td>Building land</td>
<td>2000</td>
<td>3346</td>
<td>980.00</td>
<td>3.4143</td>
<td>30.2964</td>
<td>0.0429</td>
<td>10.8046</td>
<td>0.0222</td>
<td>0.2401</td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>4339</td>
<td>1243.65</td>
<td>3.4889</td>
<td>27.1866</td>
<td>0.0455</td>
<td>9.9095</td>
<td>0.0222</td>
<td>0.2202</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>10201</td>
<td>3310.87</td>
<td>3.0811</td>
<td>15.6580</td>
<td>0.0674</td>
<td>6.2514</td>
<td>0.0222</td>
<td>0.1389</td>
</tr>
<tr>
<td>Bare land</td>
<td>2000</td>
<td>215,517</td>
<td>763,869.81</td>
<td>0.2821</td>
<td>0.3119</td>
<td>0.6665</td>
<td>0.3679</td>
<td>0.1778</td>
<td>0.0654</td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>173,395</td>
<td>764,593.75</td>
<td>0.2268</td>
<td>0.2795</td>
<td>0.6584</td>
<td>0.3289</td>
<td>0.1778</td>
<td>0.0585</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>163,938</td>
<td>744,935.87</td>
<td>0.2201</td>
<td>0.2790</td>
<td>0.6550</td>
<td>0.3247</td>
<td>0.1778</td>
<td>0.0577</td>
</tr>
<tr>
<td>Glaciers and permanent</td>
<td>2000</td>
<td>26,626</td>
<td>34,898.88</td>
<td>0.7629</td>
<td>2.3999</td>
<td>0.0877</td>
<td>1.1189</td>
<td>0.2000</td>
<td>0.2238</td>
</tr>
<tr>
<td>snow cover</td>
<td>2010</td>
<td>24,092</td>
<td>32,745.08</td>
<td>0.7357</td>
<td>2.4330</td>
<td>0.0859</td>
<td>1.1149</td>
<td>0.2000</td>
<td>0.2230</td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>19,836</td>
<td>30,114.10</td>
<td>0.6587</td>
<td>2.4006</td>
<td>0.0850</td>
<td>1.0665</td>
<td>0.2000</td>
<td>0.2133</td>
</tr>
</tbody>
</table>

In general, shrubland had the largest Ci, followed by woodland, water body, building land, grassland, wetland, glaciers and permanent snow cover, bare land, and arable land. The areas of shrubland, woodland, and water bodies were relatively small, and the Cis were relatively high. In contrast, the areas of grassland, glaciers and permanent snow cover, bare land, and arable land were relatively large, and the Cis were relatively low, showing a polygonal-shape distribution. The Ris of shrubland, woodland, and water bodies were relatively high. This may be due to the fact that shrubland, woodland, and water bodies
are vital for the ecosystem stability of the region, and increased interference from human activities leads to an unstable ecosystem in the basin and increased ecological risk.

3.2.2. Spatial Differentiation of LER

There were certain differences in the area of each LER level in the basin in different periods (Figure 4). From 2000 to 2020, the basin was dominated by the very low-, low-, and moderate-risk areas, followed by the very high- and high-risk areas (Figure 5). During the study period, the area of the very low- and moderate-risk areas rose by 89,282.5 km² and 49,172.9 km², accounting for 13.14% of the basin. The low-, high-, and very high-risk areas decreased by 15,315.06584 km², 35,701.1 km², and 87,439.8 km², respectively, accounting for 13.14% of the basin. The area of the very low-risk area gradually increased, while that of the very high-risk area was reduced. The overall LER of the basin was reduced. Therefore, from 2000 to 2020, the overall LER of the basin showed a downward trend.

![Figure 4. Area change of land-use types in the Tarim River Basin from 2000 to 2020. The lines show the conversion of different land-use types over ten-year periods, and the numbers indicate the conversion area of the land-use type.](image)

From 2000 to 2010, the very low-risk area increased from 37.50% to 42.73%, the moderate-risk area increased from 12.13% to 13.16%, and the low-, high-, and very high-risk areas reduced from 22.16%, 16.05%, and 12.16% to 19.36%, 14.88%, and 9.86%, respectively. However, during this period, the spatial changes to the risk levels were relatively small. The high- and very high-risk areas were mostly distributed in the areas near the Kunlun and Tianshan Mountains (Figure 5).

From 2010 to 2020, the very low-, low-, and moderate-risk areas increased from 42.73%, 19.36%, and 13.16% to 45.97%, 20.70%, and 16.80%, respectively, while the high- and very high-risk areas reduced from 14.88% and 9.86% to 12.66% and 3.86%, respectively. During this period, the LER of the basin decreased significantly. In addition, the northeast and southwest regions of the basin had the largest risk decline (Figure 5).

The landscape ecological risk conversion matrix (Table S1) shows that from 2000 to 2020, the area of the very low- and moderate-risk areas increased, and that of the high- and very high-risk areas were reduced. In addition, the area of the low-risk areas changed less (Figure 6). The conversion from very low risk to low risk, from low risk to moderate risk, and from very high risk to high risk were pronounced. It should be noted that from 2000 to
2020, the very high-risk and high-risk areas decreased, accounting for 8.71% and 12.41%, respectively. The conversion rate (5144.0907 km²/a) from low risk to very low risk was the largest, followed by that from high risk to moderate risk (4994.4765 km²/a).

Figure 5. Area variation of each ecological risk level for different landscapes in the Tarim River Basin from 2000 to 2020.

Figure 6. Spatial distribution of different ecological risk levels of the landscapes in the Tarim River Basin.

4. Discussion

LERA is vital for environmental management and protection, and modeling based on land-use type is one of the common methods used for LERA in the academic community. In this study, taking the Tarim River Basin as an example, Ui, Ei, and Ri were used as indicators to assess the LER of the Tarim River Basin. The results show that the area of...
the very low-risk areas in the basin gradually increased from 2000 to 2020, the area of the very high-risk areas gradually decreased, and the overall LER of the basin decreased. This indicates that the ecosystems in the Tarim River Basin have gradually recovered with the implementation of the ecological restoration project [38].

The level of LER in the basin is impacted by many natural factors and social and economic activities. Among the natural factors, climate change is the most significant influencing factor. Previous studies have shown that under climate warming, the climate in the basin has become warmer and wetter [39]. Continuous increases in temperature have accelerated glacier melting, and have also increased evaporation and precipitation [40,41]. These findings echo the findings of this study; that is, from 2000 to 2020, the area of glaciers and permanent snow cover in the basin decreased, while that of arable land and woodland increased to a certain extent. Although climate warming has brought about an increase in water resources and cultivated-land and forest-land area in the short term, in the long run, the rapid retreat of glaciers and permanent snow cover pose a great threat to water security in the basin, which may further aggravate water shortages and threaten sustainable development [41].

In the past 20 years, increased human activities have affected the environment in two ways. Firstly, population growth and socio-economic development have led to increased food demand, causing the transformation of many land-use types to arable land [42]. Similarly, in the present study, many bare lands were reclaimed from 2000 to 2020. Secondly, the environment restoration project affected land use in the basin. The comprehensive ecological restoration project was launched in 2001. By constructing reservoirs in mountainous areas, using water-saving irrigation techniques, and implementing a river management plan, regular water transmission to the area downstream of the Tarim River was achieved. This provides good water conditions for transforming arable land into woodland and grassland downstream of the Tarim River [40]. This study’s results affirm the effect of this restoration project; that is, the forest land and grassland increased from 2000 to 2020.

The research method, LERA, still needs to be continuously improved. Currently, the studies on regional LER mainly focus on the sources of risk, the evaluation systems, and the selection of management models [43]. This study clarifies the landscape pattern and ecological risks based on the results of LERA, which has a certain practical significance for ecological restoration. However, the time scale is narrow in the present study, and some long-term cumulative effects cannot be observed. In addition, this study uses a simple LERI to evaluate the LER in the basin, without considering local ecological problems. Therefore, further in-depth research will be conducted in conjunction with the actual situation of the basin.

5. Conclusions

This study assessed the LER from three aspects, including land-use patterns and transformations, temporal features of the LER, and spatial variation in the LER. From 2000 to 2020, land use significantly changed, which was the result of natural, social, and economic factors. The noteworthy changes were a decrease in glaciers and permanent snow cover caused by climate warming, and an increase in forestland and grassland induced by the ecological restoration project implemented by the government. Despite the fact that the natural environment was very fragile in the Tarim River Basin, the implementation of the ecological restoration project increased its ecological security. In the short term, the LER and the high-risk areas in the basin were reduced by the project. However, in the long run, the negative impact of climate warming is still great, which threatens water security and sustainable water use in the basin.

This study constructed the LERI based on the area proportion, Ui, and Ri of the land-use types, and only evaluated the LER of the Tarim River Basin based on the landscape spatial structure, without considering climate, topography, or socio-economic factors. Therefore, the conclusions need further validation. However, the landscape pattern of the basin is the focus of human activities and environmental management. Changes to it will
inevitably lead to changes in the ecosystem’s functioning. Therefore, it is still feasible and effective to use the landscape pattern indices to study the LER in the basin.

**Supplementary Materials:** The following supporting information can be downloaded at: [https://www.mdpi.com/article/10.3390/rs15174173/s1](https://www.mdpi.com/article/10.3390/rs15174173/s1), Table S1: Landscape ecological risk conversion matrix of the Tarim River Basin in 2000–2020.

**Author Contributions:** Conceptualization, G.W.; Methodology, G.W.; Software, Z.Z.; Validation, G.W.; Formal analysis, G.W.; Investigation, G.W., G.R. and Z.Z.; Resources, G.R. and Z.Z.; Data curation, G.R. and Z.Z.; Writing—original draft, G.W.; Writing—review & editing, G.W. and G.R.; Visualization, G.W. and G.R.; Supervision, Y.C.; Project administration, Y.C.; Funding acquisition, Y.C. All authors have read and agreed to the published version of the manuscript.

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**References**
