Landscape Ecological Risk and Drivers of Land-Use Transition under the Perspective of Differences in Topographic Gradient

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Abstract: Human activities have caused different degrees of land-use change on different topographic gradients, with impacts on the landscape and ecosystem. Effectively preventing and addressing ecological risk (ER) and achieving harmonious coexistence between humans and nature are important aspects of sustainable development. In this study, we used Gansu Province as an example, adopted five periods of land-use data in 1980, 1990, 2000, 2010 and 2020, and used the geoinformatic Tupu method and the terrain distribution index to study land-use changes under different topographic gradients, and then constructed the landscape ecological risk assessment (LERA) model based on the landscape pattern index to analyze landscape ecological risk (LER) spatiotemporal changes under different topographic gradients, and finally explored the LER driving factors using the geodetector model. The results showed that (1) the dominant land-use types were unused land and grassland, accounting for approximately 74% of the land. The situation of transferring and changing each type was more drastic. The distribution and changes in cropland and built-up land were easily found in low topographic gradient areas with low elevations and small slopes; the distribution and changes in woodland, grassland and water areas were easily found in high topographic gradient areas with high elevations and large slopes. (2) The landscape ecological risk index (LERI) was 0.018, 0.019, 0.019, 0.019 and 0.020, respectively, with spatial expressions of high in the northwest and low in the southeast. Low LER was concentrated in high topographic gradient ecological reserves; high LER was concentrated in low topographic gradient human interference areas and high topographic gradient natural environmental complex areas. (3) Natural factors mainly acted on the LER on moderate and high topographic position gradients; socioeconomic factors mainly acted on the LER on low topographic position gradients. Human interference interacted with natural factors more than human interference alone on LER. This study can provide a scientific basis for ensuring ecological security and sustainable development in areas with complex topography and geomorphology.

Keywords: land-use change; landscape ecological risk; topographic gradient; geoinformatic Tupu; geodetector; Gansu province

1. Introduction

During recent decades, due to the intensity of human activity and the rapid development of urbanization and industrialization, land use has changed dramatically. With changes in land use, the original landscape pattern changes, resulting in land degradation and a reduction in vegetation cover and biodiversity [1,2], which poses an ecological risk (ER) and, in turn, thwarts the advancement of urban ecological restoration and sustainable socioeconomic-ecological development [3].
turn affects the pattern and change in the spatial distribution of ER [5]. ER, a critical element in ecological and environmental research, assesses the extent of damage to the system based on natural disaster risk sources such as soil erosion, drought, floods, mudslides, earthquakes, etc. or anthropogenic activity risk sources such as demographic pressures, economic pressures, etc. [6–8]. ER can provide a basis for many related efforts and decision-making activities, such as regional ecological development, resource management, and environmental restoration [6]. Landscape ecological risk assessment (LERA) is one of the types of ecological risk assessment (ERA), which is usually based on the evolution of landscape patterns and ecological processes to analyze its risk status to itself and its response to external disturbance [5,6]. Hierarchy theory is a meta-theory at the pre-analytical stage [9] that classifies evaluation objects into different levels based on their different characteristics, quantities, or abilities, i.e., converting sets into levels to better analyze the objects. Therefore, by introducing this theory, LERA emphasizes the spatiotemporal heterogeneity and scale effects of ERA and achieves an integrated characterization and spatial visualization of multisource risks [10]. This method is conducive to analyzing the regional ecological environmental status and is an important significance of ER control [6,8,10].

Landscape ecological risk (LER) uses land-use types as variables to analyze the ecological consequences of landscape patterns under the influence of natural or anthropogenic factors [11] and is a valid tool for identifying ER and measuring ecological security [6,12]. Many researchers have explored the spatial and temporal characteristics of LER at different scales, in different regions, and by different methods. By integrating multiple disciplines and utilizing GIS technology [13,14], suitability methods [15], and the landscape pattern index method based on land use/land cover [5,16,17], researchers have coupled from multiple perspectives of risk sources [15,17], risk receptors [18], and evaluation models [19,20] to comprehensively analyze and assess LER. The choice of spatial scale has evolved from single to multiple scales, exploring multi-scale changes in LER by determining the appropriate spatial granularity [21]. These studies have included analyses of spatiotemporal dynamics [22,23], analyses of drivers [21], dynamic simulations under future scenarios [24] and studies of the relationships among specific factors [17,25]. In the selection of the types of evaluation objects, these studies have focused mainly on regions [26], watersheds [16,27–29], wetlands [19], coastal zones [30], oases [31], and cities [32]. In terms of evaluation methods, they mainly included the landscape pattern index method [5,16,17], the risk “source-sink” method [18], the LERA model based on ecosystem services [19,33] and constructed an LER evaluation index system from nature, societal and landscape patterns [25].

Topography has a significant impact on climate, water resources, ecosystems, and human activities. Currently, many scholars have explored the effects of topography on land-use changes [34,35], landscape patterns [4], ecosystem services [36,37], habitat quality assessments [38], ERA [5,17], and spatial patterns of rural settlements [39]. In terms of LER, topography can influence land-use structure and function [40], human activities [41], and regional landscape patterns [4] through the formation of microclimates and disturbance regimes, which in turn affect the spatial distribution of LER. In terms of topographic gradient research, the terrain distribution index was often used by most scholars to analyze the dominant distribution of research objects under different topographic gradients [5,17]. However, only a few studies have utilized the terrain distribution index to explore the spatial distribution pattern of LER under different topographic gradients [17], and in-depth studies on the changes in LER and the main driving factors under different topographic gradients are rare. Furthermore, the study described more about land-use change and LER under different topographic gradients in areas with strong human activities, economically developed areas, and rapidly urbanizing areas, while relatively few descriptions in ecologically fragile areas, agricultural and pastoral areas and urban fringe areas.

Gansu Province is a crossroads of the Loess Plateau agricultural area, the Tibetan Plateau pastoral area and the Inner Mongolia Plateau; a convergence zone of the second and third terraces; a core area for water conservation, windbreaks and sand fixation, and soil and water conservation; and an important part of the “two screens and three belts”
(Refers to the “Qinghai-Tibet Plateau Ecological Barrier”, the “Loess Plateau-Sichuan-Yunnan Ecological Barrier” and the “Northeast Forest Belt”, “Northern Sand Control Belt” and “Southern Hilly Mountain Belt”) national ecological security strategy pattern [42]; thus, it is extremely ecologically important. Due to the undulating and complex topography of Gansu Province, the terrain is high in the west and low in the east, and the whole region spans four temperature zones of subtropical, warm-temperate, mesothermal and plateau climate zones, including four dry and wet zones of arid and semi-arid, humid and semi-humid [43], and the complexity of the climate type, coupled with the frequent human activities, the ecological environment in the region has become very fragile, and ecological problems are prominent, such as vegetation degradation, soil erosion, water scarcity and serious desertification [42]. Therefore, this study proposed the following research objectives: (1) to analyze the spatio-temporal distribution characteristics of land use under different topographic gradients in Gansu Province through a long time series (1980–2020); (2) to analyze the spatio-temporal differentiation characteristics of LER under different topographic gradients; (3) to investigate the LER driving factors under different topographic gradients.

2. Materials and Methods

2.1. Study Area

Gansu Province is located in the northwestern part of China (32°11’ N–42°57’ N, 92°13’ E–108°46’ E) at the intersection of the Loess Plateau, the Tibetan Plateau and the Inner Mongolia Plateau, with a total area of approximately 425,900 km² (Figure 1). The topography of Gansu Province slopes from southwest to northeast, with a long and narrow terrain that is shaped like a dumbbell with complex and diverse landform types, including many mountainous plateaus and a few plain basins; the area has an altitude of 578–5821 m. The climate types from southeast to northwest are subtropical monsoon, temperate monsoon, temperate continental and highland alpine climates, with an average annual temperature of 0–15 ºC and an average annual precipitation of approximately 400 mm that decreases overall from southeast to northwest. Gansu Province has 12 prefecture-level cities, including Lanzhou, Tianshui and Jiayuguan, and 2 autonomous prefectures, Gannan and Linxia, with the resident population increasing from 19.18 million in 1980 to 24.92 million in 2022, an increase of 29.92%. At the end of 2022, the urbanization rate was approximately 54.19%, and the GDP reached 1.12 × 10⁴ billion CNY or 0.15 × 10⁴ billion USD.

![Study area](image_url)

Figure 1. Study area.
2.2. Data Source and Processing

The data used in this study included land-use data, natural geographic data and socioeconomic data. The specific data accuracy and sources are shown in Table 1. Among them, the land-use data were reclassified into six major categories of cropland, woodland, grassland, water area, built-up land and unused land on the basis of the existing land classification standard (GB/T21010-2017) [44] and in combination with the needs of this study, as shown in Table 2.

<table>
<thead>
<tr>
<th>Category</th>
<th>Data Type</th>
<th>Year</th>
<th>Spatial Resolution</th>
<th>Data Resource</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land-use data</td>
<td>Land use</td>
<td>Vector</td>
<td>1980–2020</td>
<td>30 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Resource and Environment Science and Data Center</td>
</tr>
<tr>
<td>Natural geographic data</td>
<td>DEM</td>
<td>Raster</td>
<td>2020</td>
<td>30 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Geospatial Data Cloud</td>
</tr>
<tr>
<td></td>
<td>Annual average temperature</td>
<td>Raster</td>
<td>1980–2020</td>
<td>1000 m</td>
</tr>
<tr>
<td></td>
<td>Annual average precipitation</td>
<td>Raster</td>
<td>1980–2020</td>
<td>1000 m</td>
</tr>
<tr>
<td></td>
<td>NDVI</td>
<td>Raster</td>
<td>1980–2020</td>
<td>1000 m</td>
</tr>
<tr>
<td></td>
<td>Soil type</td>
<td>Raster</td>
<td>1995</td>
<td>1000 m</td>
</tr>
<tr>
<td>Socioeconomic data</td>
<td>Nighttime light</td>
<td>Raster</td>
<td>1980–2020</td>
<td>0.008°/0.004°</td>
</tr>
<tr>
<td></td>
<td>GDP</td>
<td>Raster</td>
<td>1980–2020</td>
<td>1000 m</td>
</tr>
<tr>
<td></td>
<td>Population density</td>
<td>Raster</td>
<td>1980–2020</td>
<td>1000 m</td>
</tr>
</tbody>
</table>

Table 2. Classification of land-use types.

<table>
<thead>
<tr>
<th>Level 1 Type</th>
<th>Secondary Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Connotation</td>
</tr>
<tr>
<td>Cropland</td>
<td>Refers to land used for growing crops, including mature, cultivated land, newly opened land, recreational land, rotational land, grassland rotational cropland; land used mainly for growing crops for agriculture and fruit, agriculture and mulberry, and agriculture and forestry; and beach land and mudflats that have been cultivated for more than three years.</td>
</tr>
<tr>
<td>Woodland</td>
<td>Refers to forestry land where trees, shrubs, bamboo, and coastal mangroves grow.</td>
</tr>
<tr>
<td>Grassland</td>
<td>Refers to all types of grassland with a predominantly herbaceous growth and a cover of 5% or more, including scrub grassland with a predominantly pastoral growth and open grassland with a depression of less than 10%.</td>
</tr>
<tr>
<td>Water area</td>
<td>Refers to natural terrestrial waters and water facility lands.</td>
</tr>
<tr>
<td>Built-up land</td>
<td>Refers to urban and rural settlements and land for industry, mining, transportation, etc., outside of them.</td>
</tr>
<tr>
<td>Unused land</td>
<td>Currently unutilized land, including hard-to-utilize land.</td>
</tr>
</tbody>
</table>

2.3. Methods

The flowchart used in this study is shown in Figure 2.
2.3.1. Land-Use Change Analysis

The land-use dynamic attitude is an indicator that reflects the rapid change in land-use types; the greater the attitude toward land use, the faster the rate of land change and the more positively correlated the two are [45]. The land-use dynamic attitude includes the single land-use dynamic attitude (K) and integrated land-use dynamic attitude (LC), as detailed in Table 3.

Table 3. Calculation methods for this study.

<table>
<thead>
<tr>
<th>Method</th>
<th>Calculation Formula</th>
<th>Variable Interpretation</th>
<th>Connotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>$K = \frac{(U_q - U_p)}{T} \times 100%$</td>
<td>Where $K$ is the dynamic attitude of a certain land-use type in the study period; $U_q$ is the total area of a certain land-use type at the beginning of the study period; $U_p$ is the total area of a certain land-use type at the end of the study period; and $T$ is the time interval between them.</td>
<td>Reflects the rapidity of the rate of change in a particular land-use type during a certain period.</td>
</tr>
<tr>
<td>LC</td>
<td>$LC = \frac{\sum_{p=1}^{n}</td>
<td>\Delta U_{p,q}</td>
<td>}{\sum_{p=1}^{n}</td>
</tr>
<tr>
<td>Land-use transfer matrix</td>
<td>$S_{pq} = \begin{bmatrix} S_{11} &amp; \cdots &amp; S_{1k} \ \vdots &amp; \ddots &amp; \vdots \ S_{n1} &amp; \cdots &amp; S_{nk} \end{bmatrix}$</td>
<td>Where $S_{pq}$ denotes the area of the $p$th land-use type converted to the $q$th land-use type and $k$ is the number of land-use types.</td>
<td>Reflects the transformation of land-use types in a region between the areas at the beginning and end of a given period.</td>
</tr>
<tr>
<td>Topographic position index</td>
<td>$T = \log\left(\left(\frac{E}{S} + 1\right) \times \left(\frac{E}{S} + 1\right)\right)$</td>
<td>Where $T$ is the topographic position index; $E$ and $S$ are the elevation and slope, respectively, at any point in the study area; and $E$ and $S$ are the mean elevation and mean slope, respectively, of the study area.</td>
<td>The greater the elevation and the greater the slope are, the greater the topographic position index, and vice versa.</td>
</tr>
</tbody>
</table>
### Table 3. Cont.

<table>
<thead>
<tr>
<th>Method</th>
<th>Calculation Formula</th>
<th>Variable Interpretation</th>
<th>Connotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution index</td>
<td>( P = \left( \frac{A_{ie}}{A_i} \right) / \left( \frac{A_e}{A} \right) )</td>
<td>Where ( P ) is the distribution index, ( i ) is the land-use type/LER level, ( e ) is the topographic gradient level, ( A ) is the total area of the study area, ( A_{ie} ) is the area of the ( i )th land-use type/LER level on the ( e )th topographic gradient, ( A_i ) is the area of the ( i )th land-use type/LER level, and ( A_e ) is the area of the ( e )th topographic gradient.</td>
<td>Reflects the distribution of different land-use types/LER levels across the topographic gradient. When ( P &gt; 1 ), under a certain terrain factor, the ( i )th land-use type/LER level in the ( e )-level topographic gradient area has a dominant distribution, and the larger the ( P ) value is, the greater the dominance.</td>
</tr>
<tr>
<td>Geodetector</td>
<td>( q = 1 - \frac{1}{N} \sum_{z=1}^{L} \frac{N_z \sigma_z^2}{\sigma^2} )</td>
<td>Where ( q ) is the detection value for drivers of LER, taking the value of ([0, 1]), ( N ) is the number of evaluation units in the whole domain, ( N_z ) is the ( z )th evaluation unit, ( L ) is the number of driver categories, and ( \sigma_z^2 ) and ( \sigma^2 ) are the variances of the LER values for the ( z )th evaluation unit and the whole domain, respectively.</td>
<td>The ( q )-statistics were calculated and compared by factor detection in a geodetector to analyze the magnitude of the explanatory power of each driver for the spatial divergence of LER. Interaction testing was utilized to determine whether two factors interacted and to assess whether the drivers jointly enhanced or weakened the explanatory power of the spatial divergence of LER.</td>
</tr>
</tbody>
</table>

2.3.2. Land-Use Transfer Matrix

The land-use transfer matrix can provide insights into the structural characteristics of each land-use type before and after land-use transformation [46], as detailed in Table 3.

2.3.3. Geoinformatic Tupu Method

The geoinformatic Tupu method is an important method for studying spatial changes in land use [47]. By spatially overlaying the five-period land-use maps of the study area, land-use change maps were obtained for four periods: 1980–1990, 1990–2000, 2000–2010 and 2010–2020. According to the characteristics of the map changes, six patterns of map changes were summarized: stable type map, where the land-use types remained unchanged; prophase change type map, where the land-use types changed only from 1980–1990; anaphase change type map, where the land-use types changed only from 2010–2020; middle transition type map, where the land-use types changed only from 1990–2010; repeated change type map, where the land-use types regressed after changing from 1980–2020; and continuous change type map, where the land-use types changed continuously.

2.3.4. Establishment of the Landscape Ecological Risk Assessment Model

According to the connection between the landscape structure of the regional ecosystem and the ER, with reference to previous research results [48,49], this study selected the landscape disturbance index, landscape fragility index and landscape loss index to construct a LERA model (Table 4) and analyzed the size and change in the landscape ecological risk index (LERI) in the study area. To accurately evaluate the study area, the fishnet method was used to divide the study area into 20 km × 20 km fishnets, for a total of 1266 fishnets, after which the LERI in the center of each fishnet was calculated to represent the LER level of that fishnet. In this study, the LERI was calculated using Fragstats 4.2 software. Finally, the LERI was categorized into five levels: lowest risk (LERI ≤ 0.0146), lower risk (0.0146 < LERI ≤ 0.0155), moderate risk (0.0155 < LERI ≤ 0.0208), higher risk (0.0208 < LERI ≤ 0.0231), and highest risk (LERI > 0.0231).
Table 4. Calculation methods for the landscape ecological risk index.

<table>
<thead>
<tr>
<th>Index</th>
<th>Calculation Formula</th>
<th>Variable Interpretation</th>
<th>Connotation and Ecological Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landscape fragmentation index ($C_i$)</td>
<td>$C_i = \frac{n_i}{A_i}$</td>
<td>Where $n_i$ is the number of patches of landscape type $i$; $A_i$ is the area of landscape type $i$.</td>
<td>$C_i$ is used to reflect the fragmentation degree of the landscape ecosystem. It indicates the process of landscape type changing from a continuous whole patch to complex discontinuous patches under natural or human disturbance. The larger the value, the higher the fragmentation degree, the more significant the human interference and the lower the internal stability.</td>
</tr>
<tr>
<td>Landscape separation index ($N_i$)</td>
<td>$N_i = L_i \times \frac{A}{\pi}$</td>
<td>Where $A$ is the total area of the landscape type.</td>
<td>$N_i$ indicates the degree of separation between different patches in the landscape type $i$ and the total area of the evaluation unit. The larger the value is, the more complex the spatial distribution of the landscape type is and the higher the separation degree is.</td>
</tr>
<tr>
<td>Landscape dominance index ($D_i$)</td>
<td>$D_i = \frac{Q_i}{N_i} + \frac{M_i}{A_i}$</td>
<td>Where $Q_i$ is the frequency of plaques, which indicates the ratio of the number of sample areas where plaque $i$ appears to the total number of sample areas; $M_i$ is the density of plaques, which indicates the ratio of the number of plaques $i$ to the total number of plaques.</td>
<td>$D_i$ indicates the importance of patches in the landscape and, its magnitude directly reflects the size of the patches’ influence on the formation and change of the landscape pattern. The higher the value of this, the more dominant its landscape type and the higher the degree of dominance of patches in the landscape pattern.</td>
</tr>
<tr>
<td>Landscape disturbance index ($E_i$)</td>
<td>$E_i = aC_i + bN_i + cD_i$</td>
<td>Where $a$, $b$, and $c$ are the weights of $C_i$, $N_i$, and $D_i$, and $a + b + c = 1$, assigning values of 0.5, 0.3, and 0.2.</td>
<td>$E_i$ indicates the degree of disturbance of different landscape types within the study area. The larger the value, the greater the degree of disturbance and the higher the ecological risk.</td>
</tr>
<tr>
<td>Landscape vulnerability index ($F_i$)</td>
<td>Referring to the previous research result [5,16,49], each land-use type was assigned a value and then normalized.</td>
<td>The vulnerability of 6 types of land use in the study area was graded: unused land = 6, water area = 5, cropland = 4, grassland = 3, woodland = 2, built-up land = 1, and the vulnerability index of each landscape type was normalized, which was 0.286, 0.238, 0.190, 0.143, 0.095 and 0.048, respectively.</td>
<td>$F_i$ indicates the vulnerability of the ecosystems represented by different landscape types to external disturbances. The higher the value, the weaker the ability to resist external disturbances and the higher the ecological risk.</td>
</tr>
<tr>
<td>Landscape loss index ($R_i$)</td>
<td>$R_i = E_i \times F_i$</td>
<td>Where $E_i$ is the landscape disturbance index; $F_i$ is the landscape vulnerability index.</td>
<td>$R_i$ indicates the extent to which the ecosystems represented by different landscape types are disturbed by both natural and man-made disturbances.</td>
</tr>
<tr>
<td>Landscape ecological risk index ($LER_i$)</td>
<td>$LER_i = \left(\sum_{k=1}^{n} \frac{A_k}{A_k} \times R_i\right)$</td>
<td>Where $LER_i$ is the $i$th risk index of risk communities; $A_k$ is the area of the $k$-risk community category $i$ landscape; $A_i$ is the area of the $k$-risk community; $R_i$ is the landscape loss index of the type $i$ landscape.</td>
<td>Establishes a link between land-use change and landscape ecological risk and reflects the level of landscape ecological risk in the study area.</td>
</tr>
</tbody>
</table>

2.3.5. Topographic Position Index

Due to the large topographic relief and the complexity and diversity of terrain factor characteristics in the study area, the topographic position index [50], which can comprehensively reflect the characteristics of the study area in terms of elevation and slope, was selected to analyze the spatial distribution of land-use type/LER, as detailed in Table 3. Based on the actual situation in the study area, the elevation, slope and topographic position index were divided into five levels (Table 5).
Table 5. Classification of terrain factors.

<table>
<thead>
<tr>
<th>Gradient Level</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation</td>
<td>1578–1625 m</td>
<td>1625–2240 m</td>
<td>2240–2991 m</td>
<td>2991–3773 m</td>
<td>3773–5821 m</td>
</tr>
<tr>
<td>Slope</td>
<td>0–4.36°</td>
<td>4.36°–10.76°</td>
<td>10.76°–18.03°</td>
<td>18.03°–26.75°</td>
<td>26.75°–74.14°</td>
</tr>
<tr>
<td>Topographic position</td>
<td>0.11–0.36</td>
<td>0.36–0.55</td>
<td>0.55–0.73</td>
<td>0.73–0.93</td>
<td>0.93–1.51</td>
</tr>
</tbody>
</table>

2.3.6. Distribution Index

The distribution index can eliminate the effects of topographic gradient segmentation and the area differences in each land-use type/LER level [50], as detailed in Table 3.

2.3.7. Geodetector

Considering the topographic conditions, vegetation cover and climatic conditions of the study area, in this study, elevation (X1), slope (X2), annual average temperature (X3), annual average precipitation (X4), NDVI (X5) and soil type (X6) were selected as natural factors, and nighttime light (X7), GDP (X8), population density (X9) and human interference (X10) were selected as socioeconomic factors, totaling 10 drivers [21], as detailed in Table 3.

3. Results

3.1. Spatial and Temporal Distributions and Changes in Land-Use Types under Different Topographic Gradients

The spatial distribution of land-use types in the study area did not change significantly during the study period (Figure 3), showing spatial variability among the zones (Figure 4). The area of unused land accounted for the largest proportion, which was over 40% in all four years except 2020 and showed a dominant distribution in the areas of the I gradient level of elevation and slope and the I–II gradient levels of topographic position, and the distribution index decreased and then increased with the increase of each topographic gradient level. This was followed by grassland, with a total increase in area of 420.41 km² over the 40-year period, showing a dominant distribution across all topographic gradient levels and a wider range of distribution. In third place was cropland, with an overall decreasing trend in the area, with a decrease of 1.22%, showing a dominant distribution in the areas of the I–III gradient levels of elevation and the II–III gradient levels of slope and topographic position. The sum of both the woodland and water area reached more than 9% in 1980–2020, in which the dominant distribution intervals of woodland were the areas of the III–IV gradient levels of elevation and the III–V gradient levels of slope and topographic position, and its distribution index increased more with increasing gradient level of slope and topographic position. The spatial distribution of the water area was uneven, with a dominant distributions on low or high topographic gradients, indicating that topographic factors had a strong influence on the spatial distribution of the water area. The area of built-up land showed a continuously increasing trend, with a total increase of 2214.83 km², and the dominant distribution intervals were the areas of the I–II gradient levels of all elevations, slopes and topographic positions. With the increase in each topographic gradient, the area of built-up land gradually decreased, and the change in the distribution index increased, which indicated that the spatial distribution of built-up land was subject to the stronger constraints of the terrain factor.
spectrally. The transferred in area of grassland reached 7026.04 km², with the largest
contribution from cropland due to the implementation of the policy of returning farmland
to forests. The transferred out area of grassland reached 6605.54 km², with 73% converted
to cropland and unused land. Woodland was mainly transformed from grassland, and the
transferred out area was 5305.72 km², with 73% converted to chopped land and unused land.
Woodland was mainly transformed from grassland, and the
transferred out area was 1226.21 km². Built-up land was mainly transformed from cropland,
and the transferred in area was 1232.80 km². There were also large variations in transfer
in and out over time. In terms of transfer in, between 1980–1990, the land-use types with the
most and least areas transferred in were unused land and built-up land, respectively, and grassland and water area in the remaining three periods. In terms of transfer out, between 2000–2010, the land-use types with the most and least areas transferred out were cropland and water area, respectively, and grassland and built-up land in the remaining three periods.

Figure 3. Spatial distribution and area proportion of land-use types in Gansu Province from 1980 to 2020.

Figure 4. Distribution index of land-use types on each elevation gradient, slope gradient and
topographic position gradient in Gansu Province from 1980 to 2020. (a) Distribution index of land-use
types over elevation gradients in Gansu Province from 1980 to 2020. (b) Distribution index of land-use
types over slope gradients in Gansu Province from 1980 to 2020. (c) Distribution index of land-use
types over topographic position gradients in Gansu Province from 1980 to 2020.

The LC over the four periods was 0.009%, 0.023%, 0.068%, and 0.041%, respectively,
with the fastest rate of change in built-up land, which reached a maximum of 3.937% between 2010 and 2020 (Figure 5f). The transformation between categories occurred mainly between cropland and grassland, built-up land, and unused land (Figure 5a–e). Overall, from 1980 to 2020, grassland was the type with the most area transferred in and out, respectively. The transferred in area of grassland reached 7026.04 km², with the largest
contribution from cropland due to the implementation of the policy of returning farmland
to forests. The transferred out area of grassland reached 6605.54 km², with 73% converted
to cropland and unused land. Woodland was mainly transformed from grassland, and the
transferred in area was 1232.80 km². Built-up land was mainly transformed from cropland,
and the transferred in area was 1454.30 km². There were also large variations in transfer
in and out over time. In terms of transfer in, between 1980–1990, the land-use types with the
most and least areas transferred in were unused land and built-up land, respectively, and grassland and water area in the remaining three periods. In terms of transfer out, between 2000–2010, the land-use types with the most and least areas transferred out were cropland and water area, respectively, and grassland and built-up land in the remaining three periods.
Figure 4. Distribution index of land-use types on each elevation gradient, slope gradient and topographic position gradient in Gansu Province from 1980 to 2020. (a) Distribution index of land-use types over elevation gradients in Gansu Province from 1980 to 2020. (b) Distribution index of land-use types over slope gradients in Gansu Province from 1980 to 2020. (c) Distribution index of land-use types over topographic position gradients in Gansu Province from 1980 to 2020.

The LC over the four periods was 0.009%, 0.023%, 0.068%, and 0.041%, respectively, with the fastest rate of change in built-up land, which reached a maximum of 3.937% between 2010 and 2020 (Figure 5f). The transformation between categories occurred mainly between cropland and grassland, built-up land, and unused land (Figure 5a–e). Overall, from 1980 to 2020, grassland was the type with the most area transferred in and out, respectively. The transferred in area of grassland reached 7026.04 km², with the largest contribution from cropland due to the implementation of the policy of returning farmland to forests. The transferred out area of grassland reached 6605.54 km², with 73% converted to cropland and unused land. Woodland was mainly transformed from grassland, and the transferred in area was 1232.80 km². Built-up land was mainly transformed from cropland, and the transferred in area was 1454.30 km². There were also large variations in transfer in and out over time. In terms of transfer in, between 1980–1990, the land-use types with the most and least areas transferred in were unused land and built-up land, respectively, and grassland and water area in the remaining three periods. In terms of transfer out, between 2000–2010, the land-use types with the most and least areas transferred out were cropland and water area, respectively, and grassland and built-up land in the remaining three periods.

Figure 5. Transfer and dynamic changes of land-use types in Gansu Province from 1980 to 2020. (km²). (a–e) Changes in area transfers by land-use types in Gansu Province from 1980 to 2020. (f) The dynamic attitude of each land-use type in Gansu Province from 1980 to 2020.

The spatial distribution of land-use change, TUPU, showed some variability with different topographic gradient levels (Figures 6 and 7). The area in the stable type map accounted for the largest proportion, which was mainly dominated by unused land, grassland and cropland remaining unchanged, with a share of 93.77%. The stable type map was less constrained by topographic factors because the structure of land-use types does not change drastically due to a single factor (topography). The middle transition type map was dominated by cropland converted to grassland, with an area of 3787.20 km². It was predominantly distributed in the areas of the I gradient level of elevation, the II–IV gradient levels of slope and the III–IV gradient levels of topographic position, which were more influenced by slope and less sensitive to changes in elevation. The anaphase change type map was dominated by the conversion of grassland in 1980 to cropland in 2020, which accounted for 14.25% of the area of this type and showed a dominant distribution of the I gradient level on each topographic gradient. The dominant distribution areas were located in the areas of the I–III gradient levels of elevation, the II–V gradient levels of slope, and the III–IV gradient levels of topographic position, which were affected by both elevation and slope and the distribution gradually converged with the increase in the gradient level of topographic position. Due to the implementation of the policy of returning farmland to forests, the repeated change type map and continuous change type map were mainly in the conversion between cropland and grassland, with the area accounting for 1.11% of the total area of the study area. The dominant distribution areas were located in the areas of the I–III gradient levels of elevation, the II–V gradient levels of slope, and the III–IV gradient levels of topographic position, which were affected by both elevation and slope and the distribution gradually converged with the increase in the gradient level of topographic position. The area of the prophase change type map was the smallest and was mainly characterized by the conversion of grassland in 1980 to unused land in 1990, and then remained unchanged, which was dominantly distributed in the I gradient level on each topographic gradient.
Figure 6. Information on the land-use change, TUPU, in Gansu Province from 1980 to 2020. (a) Spatial distribution of land-use change, TUPU, in Gansu Province from 1980 to 2020. (b) Area proportion of land-use change, TUPU, in Gansu Province from 1980 to 2020.

Figure 7. Distribution index of land-use change, TUPU, on each elevation gradient, slope gradient and topographic position gradient in Gansu Province. (a) Distribution index of land-use change, TUPU over elevation gradients in Gansu Province. (b) Distribution index of land-use change, TUPU over slope gradients in Gansu Province. (c) Distribution index of land-use change, TUPU over topographic position gradients in Gansu Province.

3.2. Spatial and Temporal Distribution and Changes in Landscape Ecological Risk under Different Topographic Gradients

The LERI in the study area was 0.018, 0.019, 0.019, 0.019 and 0.020 in 1980, 1990, 2000, 2010, and 2020, respectively, with the index increasing each year. The LER was mainly dominated by moderate LER and the highest LER, with spatial patterns of high in the northwest and low in the southeast (Figure 8). The distribution of different levels of LER varied significantly across the topographic gradient (Figure 9). The area of the lowest LER area showed a trend of first decreasing and then increasing, mainly concentrated in the moderate and highest topographic position gradient areas with higher elevations and wider distribution ranges of slopes. The distribution indices of the slope gradient and topographic position gradient increased with increasing gradient level and exhibited the most advantageous distribution at the V gradient level. The lower LER area decreased by $1.22 \times 10^4 \text{ km}^2$ over the 40-year period, and the dominant distribution areas were mainly in the moderate and higher topographic position gradients with low elevations and moderate slopes. The distribution index increased and then decreased with increasing gradient levels. The moderate LER area decreased by a total of 4% over the 40-year period, and the dominant distribution area was wider, with a slower degree of change in the distribution index. The area with a higher LER decreased the most, by $3.12 \times 10^4 \text{ km}^2$. The highest LER was the only increase in area and had the largest change, totaling $5.78 \times 10^4 \text{ km}^2$. The highest LER and highest LER showed a dominant distribution in areas with low topographic position gradients with the lowest or highest elevations and small slopes.
As shown in Figure 10, the unchanged LER area had the largest proportion, approximately 68.80%, showing a dominant distribution in the I and IV gradient levels of elevation and the III–IV gradient levels of slope and topographic position, which were more influenced by slope and less sensitive to changes in elevation. This indicates that the LER easily maintained its stability on higher topographic gradients where human activities were infrequent. The proportion of the increased LER area was approximately 28.12%, showing a dominant distribution in the V gradient level of elevation, the I gradient level of slope and the I, II and V gradient levels of topographic position. This indicates that increased LER is prone to occur in areas with frequent human activities and fragile ecological environments. The area of decreased LER accounted for the smallest proportion, at only 3.08%, and the dominant distribution areas were all on the II–III gradient levels of elevation, slope and topographic position. This indicates that human activities are not frequent and that there is a large amount of cropland and grassland in the lower or moderate topographic gradient area, which decreases the LER in this area.
was greater than 0.50, indicating that the growth of vegetation affects landscape types, 
the explanatory power of the NDVI for the LER at different topographic position gradients 
population density and nighttime light for the LER increased during the 40-year period on 
position gradients. Among them, human interference had the greatest explanatory power 
influence. This indicates that elevation, annual average temperature and annual average pre-
growth of vegetation, which reflects the health of the ecosystem and thus influences the LER. 
altering the natural landscape and influencing the LER. In addition, NDNI represents the 
greater changes in the annual average temperature and elevation, while the slope had little 
growth of vegetation, which reflects the health of the ecosystem and thus influences the LER. 
and annual average precipitation can act to varying degrees on vegetation growth and 
influence. Along the III–V gradient levels of topographic position, natural factors gradually 
ecological risk level change in Gansu Province from 1980 to 2020. (a2) Area proportion of landscape ecological 
risk level change in Gansu Province from 1980 to 2020. (a3) Distribution index of landscape ecological 
risk level change in Gansu Province from 1980 to 2020.

3.3. Drivers of Landscape Ecological Risk under Different Topographic Position Gradients

3.3.1. Single-Factor Detection

Natural factors had the strongest explanatory power for the evolution of LER on the 
III–V gradient levels of topographic position, and socioeconomic factors had the strongest 
explanatory power for the evolution of LER on the I–II gradient levels of topographic 
position (Figure 11). The explanatory power of human interference, the NDVI, and annual 
average precipitation for LER were consistently among the top three across topographic 
position gradients. Among them, human interference had the greatest explanatory power 
for LER across all topographic position gradient levels, reaching more than 0.70, indicating 
that human activities play a dominant role in the spatial evolution of LER at small scales. 
The explanatory power of the NDVI for the LER at different topographic position gradients 
was greater than 0.50, indicating that the growth of vegetation affects landscape types, 
thus affecting the LER in the study area. In addition, the explanatory power of GDP, 
population density and nighttime light for the LER increased during the 40-year period on 
the I–II gradient levels of topographic position. This indicates that socioeconomic factors 
dominate the spatial evolution of LER with the acceleration of the urbanization process 
on the low topographic position gradient, but natural factors also have a certain degree of 
influence. Along the III–V gradient levels of topographic position, natural factors gradually 
dominated, with greater changes in the annual average temperature and elevation, while 
the slope had little influence. This indicates that elevation, annual average temperature 
and annual average precipitation can act to varying degrees on vegetation growth and 
aricultural production, thus altering the natural landscape and influencing the LER. 
In addition, NDNI represents the growth of vegetation, which reflects the health of the 
ecosystem and thus influences the LER.

Figure 11. Single-factor detection results of landscape ecological risk drivers under different topographic position gradients in Gansu Province from 1980 to 2020.
3.3.2. Interaction Detection

The results of the two-factor interaction probes showed that the interactions of the random two factors were both larger than the single-factor effects, and the probes all showed two-factor enhancement and nonlinear enhancement effects. This result indicated that the LER changes were not determined by a single factor but were the result of the combined effects of the driving factors, confirming that the LER changes were a complex process of factor interactions (Figure 12). From 1980 to 2020, the explanatory power of $X_{10}$ (human interference) ∩ $X_3$ (annual average temperature)/$X_4$ (annual average precipitation)/$X_5$ (NDVI)/$X_6$ (soil type) was greater on the I–II gradient levels of topographic position. This result indicated that after the interaction of human interference with natural factors on the gradient of low topographic positions, especially with annual average precipitation and the NDVI, the explanatory power for the LER was significantly greater. The explanatory power of $X_{10}$ (human interference) ∩ $X_1$ (elevation)/$X_2$ (slope)/$X_3$ (annual average temperature)/$X_4$ (annual average precipitation)/$X_5$ (NDVI) was greater on the III–V gradient levels of topographic position. The explanatory power of the interaction between human interference and elevation and slope gradually increased with increasing topographic position gradient.

Figure 12. Interaction factor detection results of landscape ecological risk drivers under different topographic position gradients in Gansu Province from 1980 to 2020 ($X_1$: elevation; $X_2$: slope; $X_3$: annual average temperature; $X_4$: annual average precipitation; $X_5$: NDVI; $X_6$: soil type; $X_7$: nighttime light; $X_8$: GDP; $X_9$: population density; and $X_{10}$: human interference).
4. Discussion

4.1. Land-Use Change under Different Topographic Gradients

The degree of land-use change in the study area during the study period was first large and then small, and the changes in the spatial distribution of land-use types were relatively small, but the overall change in area over time was characterized by a decrease in cropland and unused land, and an increase in woodland, grassland, water area and built-up land. The main direction of transfer between the land-use types changed between 1980–2000 and 2000–2020, changing from grassland to cropland and woodland to grassland in the earlier period to cropland to grassland and grassland to woodland in the later period. The former conversion of woodland to grassland was caused by factors such as overexploitation in certain areas or climate change, which led to land desertification and, thus, the gradual disappearance of forest vegetation [51,52], which eventually became grassland or desert. In contrast, the conversion of cropland to grassland and grassland to woodland in the later stage was the result of returning farmland to forest and natural succession [52,53]. Changes in land-use types are never caused by a single factor but occur as a result of a combination of factors [54]. From 1980 to 2000, under rapid population growth and technological underdevelopment, people participated in agricultural farming to meet their survival and development needs by reclaiming wasteland or destroying grassland and woodland, and indiscriminate deforestation and overgrazing ensued [55]; thus, the land-use types during this period were characterized by an increase in the area of cropland and reduced areas of grassland and unused land, resulting in greater damage to the ecological environment in the region and a gradual increase in risk. Since the return of farmland to forest began to be implemented in the study area in 1999, significant results have been achieved over the past 20 years. In addition, the implementation of key projects such as natural forest protection and the Three–North Protective Forest has restricted agricultural activities [56]. Due to the superposition of natural, social and economic factors, such as steep slopes, barren and low–yield areas, and lifestyle changes, some farmers have given up farming and have chosen to work or settle down [57], resulting in the phenomenon of land abandonment. In this stage, the area of cropland greatly decreased, and the areas of woodland and grassland gradually increased. In summary, the land-use mode in the study area has changed from a simple exploitation mode to a conservation and ecological construction mode.

Topographic factors are important factors affecting hydrothermal conditions and human activities and largely determine the basic spatial distribution pattern of land use [4,40,58]. Croplands in the study area have a dominant distribution across low and moderate topographic gradients. Grasslands have distributional advantages on multilevel topographic gradients. Multiple dominant land-use types coexisted across the topographic gradient, except for the absolute dominance of woodland on the high topographic gradient. Human farming, engineering and construction activities are simultaneously constrained by topographic factors [41], and land-use types (cropland, water area and built-up land) closely related to human production and life are distributed in areas with low topographic position gradients, lower elevations and smaller slopes. With the implementation of policies such as the construction of the Three-North Protective Forest System and the policy of returning farmland to forests (grasslands) [56], cropland and unused land have shifted to woodland or grassland, which has led to a continuous expansion of woodland area into the moderate topographic gradient area. This enriches, to some extent, the land-use types and optimizes the land-use structure in the moderate and high topographic gradients. In summary, the spatial distribution of cropland and built-up land in the study area is greatly influenced by topographic factors and tends to be distributed in areas with low topographic position gradients, low elevations and small slopes, i.e., plains and low gently hilly areas. The spatial distribution of woodland, grassland and water area in the study area is less influenced by topographic factors and tends to be distributed in areas with high topographic position gradients, high elevations and large slopes, i.e., mountainous and hilly areas.
4.2. Landscape Ecological Risk and Drivers under Different Topographic Gradients

Topographic features determine land-use modes, land-use structures and land-use patterns [58], and land-use changes are closely related to LER [59]. The unused land and built-up land areas in the study area mostly had the highest LER and higher LER, while the cropland, grassland and woodland areas were mainly dominated by moderate LER, lower LER and the lowest LER, respectively. Most of the area in the northwestern part of the study area was unused land, including hard-to-utilize land, sandy land, Gobi, saline and alkaline land, marshy land and bare land, etc., with sparse surface vegetation, low biodiversity and poor resistance to external disturbances [52], coupled with low precipitation and high evapotranspiration; thus, the ecological environment in this area is relatively fragile, and most of the LER is maintained at a high level. In contrast, the land-use types in the southeastern part of the study area are diverse and mainly consist of cropland, grassland and woodland, with a high degree of land cover continuity and a low landscape fragmentation index, resulting in a low landscape disturbance index and a low vulnerability index, which puts the LER of the region at a low level.

The study area has a large topographic relief, which makes the LER based on land-use change a causal factor that shows a more complex spatial distribution with the topographic gradient. This is demonstrated by the fact that areas with low topographic gradients are often accompanied by higher risk and the highest risk. This is due to the flat topography of the area, which makes it suitable for built-up land development, facilitates road construction, has high transportation access, and has a high concentration and frequency of human activities. To satisfy human living and production needs, human beings have caused great changes in land-use patterns and land-use landscape patterns in the region [60], the most prominent of which is the rapid expansion of cropland and built-up land in the study area. The landscape types are interlaced [61], with high landscape separation, weak connectivity, and serious fragmentation, disrupting the regional ecological environment and leading to a high level of regional LER. Moderate LER is widely distributed across the topographic gradient. Areas with high topographic gradients are home to dominant distributions of the lowest and lower LER. Due to the limitations of topographic and climatic factors [62], the woodlands and grasslands in the study area are mainly distributed in areas with high topographic gradients, contiguous distributions of land-use types, high landscape connectivity, low fragmentation, and low likelihood of being prone to LER, which are mainly low risk.

The LER patterns and changes in the study area are the result of the combined effects of nature, human activities and landscape patterns [63]. From a relatively static ground perspective, natural factors such as topography and climate dominate the influence of the LER in the study area [64], especially the NDVI, annual average temperature and annual average precipitation, which all affect the LER at different topographic gradients. Socioeconomic activities resulting from human development and utilization are relatively secondary, but human interference has the greatest impact on LER at small scales [64]. From the perspective of the dynamics of LER transfer, the driving role of socioeconomic factors is more significant [65], which is reflected in human interference in different directions and to different degrees. Human interference generally occurs in areas with low topographic gradients, resulting in an increase in LER and protecting the health of the natural environment in areas with high topographic gradients, which decreases the LER in these regions. In summary, natural and socioeconomic factors affect the LER and its changes at different topographic gradients, such that a high LER occurs in the low topographic gradient human interference area and high topographic gradient natural environmental complex area [17], and a low LER occurs in the high topographic gradient ecological reserves.

4.3. Landscape Ecological Risk Mitigation Strategies Based on Land Use and Topographic Gradients

The low topographic gradient areas in the study area are dominated by high LER–dominant areas for cropland, water area and built-up land. The region is relatively flat, and the expansion of built-up land has led to the fragmentation of farmland patches, af-
fecting the cultivation of paddy fields and drylands and destroying the linkages that the agricultural biological communities have jointly established with their surrounding nature and socio–economies, which is manifested in the decline of the self–regulation capacity and internal stability of farmland ecosystems [66], and thus a relatively fragile ecological environment. Therefore, regions should promote comprehensive landscape management, reduce landscape fragmentation and enhance landscape integrity and continuity. In addition, with sustainable development as the goal, the scale of land development should be reasonably controlled, and all kinds of activities should be carried out according to local conditions to find a balance between protection and utilization [67]. Protecting the regional ecological environment and simultaneously satisfying the needs of social development can ensure the sustainable development of the region. The moderate topographic gradient area is an area of low and moderate LER dominance. On the premise of protecting the original natural resources, regions should further increase vegetation cover through ecological protection projects such as fencing, grazing bans and grazing rests and should fully utilize and enhance the function of ecological barriers; comprehensively consider the extent of towns and ecological land use; plan ahead to construct a regional ecological security pattern [25]; and establish a comprehensive ecological compensation system to improve regional ecosystem resilience [68]. The high topographic gradient areas are dominated by low LER–dominant areas for woodland and grassland. As most of the land-use types in the region are dominated by woodlands and grasslands, the habitat quality is good, and the ecological role is strong; these areas play important roles in ecosystem structure and function and biodiversity conservation [68], which is conducive to reducing LER. Therefore, these areas should continue to carry out ecological and environmental protection and monitoring, maintain the integrity and connectivity of the landscape within low–risk areas, and avoid an increase in LER within them; additionally, policies for sealing off the mountains and cultivating the forests should be implemented, the principles of ecological prioritization should be followed, deterioration caused by human activities should be avoided, and the original ecological outlook should be protected.

4.4. Limitations and Prospects

This study evaluated the land-use changes, LER evolution process and drivers in the study area from 1980 to 2020 based on a topographic gradient to provide support for regional ecological environmental protection and ecological environmental management, but it lacks the prediction and warning of future LER. For this reason, the focus of the next step of the study should be to combine the model predictions to explore the LER distribution law under different scenarios in the future and improve the effectiveness and comprehensiveness of the LER evaluation, with a view to providing scientific and effective risk prevention and control suggestions. In addition, the spatial resolution of some of the obtained data is low due to the limitations of the data source; therefore, future research needs to focus on improving more accurate databases.

5. Conclusions

This study analyzed land-use change, LER spatial and temporal change characteristics, and LER driving factors under different topographic gradients in the study area from 1980 to 2020 with the help of spatial statistical analysis, LERA and terrain distribution index. The following conclusions were drawn: (1) The land-use types were dominated by unused land and grassland, which accounted for approximately 74% of the total area. There was an overall decrease in the area of cropland and unused land and an overall increase in the area of woodland, grassland and built-up land. The distribution and changes in cropland and built-up land mainly occurred in areas with low topographic gradients, and the distribution and changes in woodland, grassland and water areas mainly occurred in areas with high topographic gradients. (2) The overall trend of the LERI was upward, dominated by moderate LER and the highest LER, with spatial expressions of high in the northwest and low in the southeast. The lowest and lower LER had a dominant distribution in areas
with high topographic gradients; the higher and highest LER were mainly distributed in areas with low topographic gradients or high-elevation gradients areas. (3) Natural factors had the strongest explanatory power for the evolution of the LER on moderate and high topographic position gradients, and socioeconomic factors had the strongest explanatory power for the evolution of the LER on low topographic position gradients. The explanatory power of human interference, NDVI and annual average precipitation for LER was consistent among the top three across topographic position gradients. Human interference interacted with natural factors more than human interference alone on LER.

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