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Original Research

Terrain Gradient Effect of Land Use and Its Driving Factors in the Qinghai-Tibet Plateau

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Abstract

Terrain is an important influencing factor of land use/cover change, it is of great significance to study the relationship between land use and terrain gradient. To analyze the relationship between elevation, slope, aspect, terrain niche index (TNI), topographic relief (TR), and land use, this study took the Qinghai-Tibet Plateau (QTP) as the research area, adopted the five periods of land use data from 1980 to 2015 and Digital Elevation Model (DEM) data, using the topographic distribution index and the comprehensive index of land use degree. The results were as follows: (1) The optimal calculation window size for TR in the QTP was 31.4841 km^2. (2) The terrain gradient effect of grassland, built-up land, cropland, forest, and water body was significant. Unused land mainly affected the comprehensive index of land use degree. (3) The comprehensive analysis of TNI could better analyze the impact of terrain on land use. (4) The main driving factors were natural and human factors. The results revealed the terrain gradient effect of land use in the QTP, which could provide a reference for overall land planning, management, and sustainable use of land resources.

Keywords: land use, terrain gradient, sustainable use, Qinghai-Tibet Plateau, GIS

Introduction

Land use/cover change (LUCC) is an integral part of global environmental change and sustainable development. Through the use of natural resources related to land, human beings change the coverage of the earth's land surface, which has a significant impact on the global climate [1, 2], hydrology [3], carbon cycle [4], and biodiversity [5]. At present, it has become one of the research hotspots of world environmental studies [6, 7]. Since the 1990s, the two major international organizations, "International Geosphere-Biosphere Program" (IGBP) and "International Human Dimensions Programme on Global Environmental Change" (IHDP), have jointly formulated LUCC scientific research plans as one of the core projects of research [8]. On this basis, the global land project (GLP) was launched in 2005, which significantly strengthened human understanding of regional and international land systems. In summary, LUCC has received extensive attention. Terrain is an important influencing factor of LUCC, by acting on the surface of material migration and participate in the form of energy conversion in a certain extent determines the regional land use change direction and speed. Therefore, it is of great significance to study the relationship between land use and terrain gradient. The current

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research on the relationship between land use and terrain gradient mainly focused on terrain factors such as elevation, slope, and aspect. Lu studied four typical mountainous areas on the southern slope of the middle part in the Himalayas and obtained the relationship between the spatial distribution characteristics of land use and elevation, slope [9]. Liu and Li studied the relationship between the spatial distribution of land use and elevation, slope, aspect in Hangzhou [10]. The results showed that terrain had a significant impact on the distribution pattern of land use. Kelarestaghi and Jeloudar studied the Lajimrood Drainage Basin in northern parts of Iran. The results showed that elevation, slope, and aspect were important influencing factors of land use [11]. However, there were few related types of research on the comprehensive analysis of the relationship between regional terrain gradient and land use by TNI and TR. In addition, the period, research scope, and research area of land use change were small [12, 13]. Moreover, there were relatively few studies on land use analysis of complex mountainous areas and ecologically fragile areas using terrain factors. The QTP is the highest plateau in the world, with a fragile ecological environment and complex terrain. The restriction of terrain factors on land use is very prominent. Wu et al. studied the impact of terrain on ecosystem services [14]. Cui et al. only studied the impact of terrain on forest, and the research scope was not the entire QTP, but a very small part of it [15].

In this study, five periods of land use data in 1980, 1990, 2005, 2010, 2015 and DEM data in the QTP were used to study terrain gradient effect of land use. Firstly, slope and aspect were calculated based on DEM data, TNI was calculated based on elevation and slope, and the optimal grid window size was determined by means of change-point analysis. Then, the relationship between elevation, slope, aspect, TNI, TR, and land use was analyzed by using the topographic distribution index and comprehensive index of land use degree. Finally, the driving factors were analyzed from the natural and human aspects, which could provide the scientific basis for overall land planning, management, and sustainable use of land resources in the QTP.

Materials and Methods

Study Area

The QTP is the largest plateau in China and the highest in the world, with an average altitude of >4000 m, which is known as the "roof of the world". It is between 26°00′-39 47′N and 73°19′-104°47′E, about 2800 km long from east to west and 300-1500 km wide from north to south. The total area in China exceeds 250×10^4 km^2. In terms of administrative divisions, the QTP includes Tibet and Qinghai Province, parts of Sichuan, Xinjiang, Gansu, and Yunnan Province (Fig. 1).

The QTP has strong sunshine and significant temperature differences, and the annual average temperature decreases from 20ºC in the southeast to below -6ºC in the northwest. The QTP is rich in water resources, in the form of rivers, lakes, glaciers, groundwater and other water bodies. The QTP has a large height difference, complex terrain, and various types of land use, primarily grassland and unused land, with less cropland, mainly concentrated in river valleys.

Data Sources and Processing

The land use data with 1-km spatial resolution acquired from the Institute of Geographic Sciences of Chinese Academy of Sciences (http://www.igsnrr.ac.cn) and Digital Elevation Model data with 30-m spatial resolution (which was resampled into 1-km spatial resolution) from Geospatial Data Cloud (http://www.gscloud.cn) were used in this study. The Albers conical equal-area projection was used with WGS_1984 datum. According to LUCC classification system, the land use classification was classed into six categories: grassland, built-up land, cropland, forest, water body, and unused

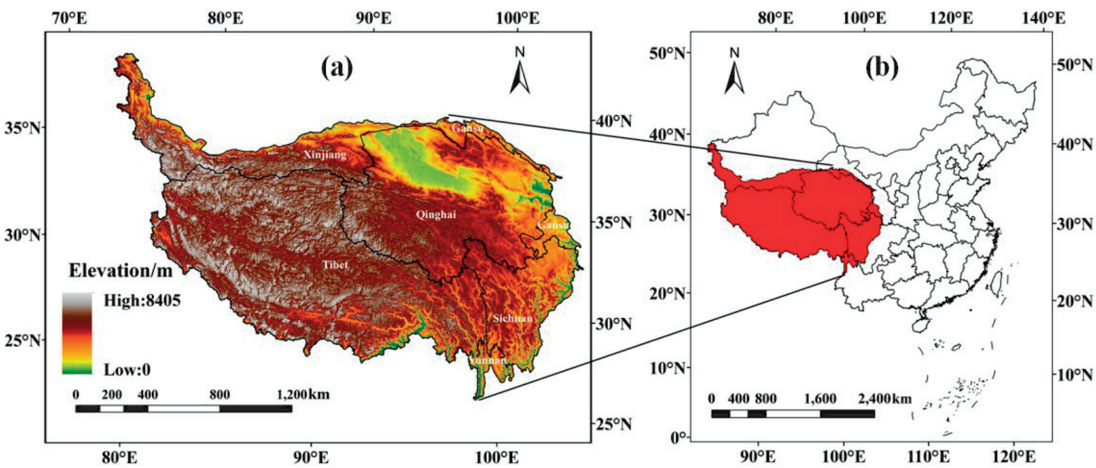

Fig. 1. The elevation a) and location b) of the Qinghai-Tibet Plateau.

land (the accuracy of land use classification data reached more than 93 percent [16]). According to the DEM data, it could be seen that the terrain in the study area was undulating, so the elevation was divided into ten levels: 0-2000 m, 2000-2500 m, 2500-3000 m, 3000-3500 m, 3500-4000 m, 4000-4500 m, 4500-5000 m, 5000-5500 m, 5500-6000 m, >6000 m.

According to "the technical regulations of the third national land survey of the People's Republic of China" and the actual situation of the study area, the slope was divided into 10 grades: 0-2°, 2-4°, 4-6°, 6-10°, 10-15°, 15-20°, 20-25°, 25-30°, 30-35°, >35°. The aspect was divided into five grades: flat slope (-1°), shady slope (315°-45°), semi-shady slope (45°-135°), sunny slope (135°-225°) and semi-sunny slope (225°-315°) (Fig. 2).

Research Methods

Terrain Niche Index

A single terrain factor cannot comprehensively reflect the impact of terrain on land use [17], combining elevation and slope to form a TNI can reveal the spatial distribution characteristics of land use patterns on terrain gradient [18], and comprehensively reflect the impact of terrain on land use, the formula is [19-21]:

$$T = Ln[(E/\bar{E} + 1)* (S/\bar{S} + 1) \qquad (1)$$

where T is the TNI, E is the elevation of any grid, $\bar{E}$ is the average elevation of the area where the grid is located, S is the slope of any grid, $\bar{S}$ is the average slope of the area where the grid is located. The higher TNI reflects that the elevation and slope of the area are both large, and the medium TNI reflects that the elevation of the area is large but the slope is small, or the slope is large but the elevation is small, and the lower TNI reflects the elevation and slope of the area are both small [22, 23].

Topographic Distribution Index

To eliminate the area difference between the levels of different terrain factors and the area difference between different land use types, in this study, standardized and dimensionless topographic distribution index is introduced to describe the distribution of varying land use types on different terrain gradients, the formula is as follows [24]:

$$P_{ie} = (A_{ie}/A_i)(A_e\ /A) \qquad (2)$$

where P_{ie} represents the topographic distribution index, e represents the terrain factor, A_{ie} represents the area of the i land use type in a certain grade under e terrain factor, A_i represents the total area of the i land use type in the research area, A_e represents the total area of a certain grade under e terrain factor, and A represents the total area of the research area. If P_{ie}>1, this type of land has a distribution advantage in a certain level of terrain factors, and the larger P_{ie} is, the more pronounced the distribution advantage is. If P_{ie}<1, this type of land has a distribution advantage in a certain level of terrain factors, and the smaller P_{ie} is, the more pronounced the distribution disadvantage is.

Topographic Relief

The TR is the difference between the maximum elevation and the minimum elevation in a certain area, which is a macroscopic index. It can reflect local topographic fluctuations, objectively and directly describe the topographic features of a region. The TR calculated by different sizes of grid units is varying, so determining the size of the optimal grid window is the key to calculate the TR. In this study, the window analysis method was adopted [25]. The Python module was used to extract the average TR T_n of the grid with n× n pixel size (n = 2, 3, 4..., 30, 31, 32) window in sequence and taken as ordinate, the area of the grid window of different sizes as the abscissa, made a curve and fitted it. Previous studies had shown that the curve was a logarithmic curve [26], and there was only one "inflection point" from steepness to slowness on the curve, and the grid window size corresponding to this point was the optimal grid window size. In this study, the mean change point analysis in statistics [25] was used to determine the optimal grid window size.

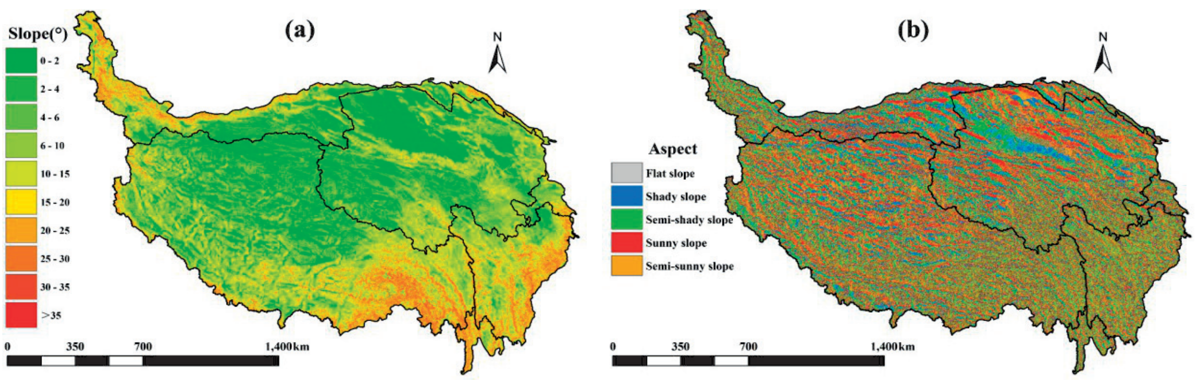

Fig. 2. The slope a) and aspect b) of the Qinghai-Tibet Plateau.

The specific calculation process is as follows:

(1) The formula is used to obtain the average TR per unit area column R_n of different grid window sizes.

$$R_n = T_n/S_n \tag{3}$$

where R_n, T_n and S_n are the average TR of unit area, average TR, and the area of different grid window sizes.

(2) Take the logarithm of sequence R_n to get sequence X_i (i = 1, 2, 3…, 29, 30, 31), then calculate the arithmetic mean $\bar{X}$ and the sum of squared deviations S.

$$S = \sum_{l=1}^{31}(X_l - \bar{X})^2 \tag{4}$$

(3) Let j = 2…, 31, for each j, set the sequence X_i is divided into two sub sequences, the first segment sequence $K_1\{X_1, X_2, .., X_{j-1}\}$ and the second segment sequence $K_2\{X_j, X_{j+1}, .., X_{31}\}$, then calculate the arithmetic mean of the two sequences $\overline{X_{K1}}$ and $\overline{X_{K2}}$, the sum of squared deviations S_{K1}, S_{K2} and S_K.

$$S_{K1} = \sum_{l=1}^{j-1}(X_l - \overline{X_{K1}})^2 \tag{5}$$

$$S_{K2} = \sum_{l=j}^{31}(X_l - \overline{X_{K2}})^2 \tag{6}$$

$$S_K = S_{K1} + S_{K2} \tag{7}$$

(4) Taking the value of $S–S_K$ as the ordinate and the point i as the abscissa to make a curve, finding out the number of points corresponding to $S–S_K$ reaching the maximum value, which is the required inflection point from steep to slow, and then get the optimal grid window size of TR.

The Comprehensive Index of Land Use Degree

As different land use types have different impacts on the environment, they can be divided into four grades from low to high. The comprehensive index of land use degree can be calculated according to Formula (8), which can be used to study the land use change in the study area during a certain period, the formula [27, 28] is as follows:

$$L = 100 * \sum_{i=1}^{n} A_i * C_i \tag{8}$$

where L is the comprehensive index of land use degree, which is between 100 and 400. The closer L is to 400, the higher the land use degree is. A_i is the grade index of the i land use type, unused land is 1; forest, grassland, water body are 2; cropland is 3; built-up land is 4. C_i is the area percent of the i land use type [29].

Results

Elevation Gradient Effect of Land Use

It could be seen from Fig. 3 that there were apparent differences in elevation gradients of land use types in the QTP. Grassland had dominant distribution only in elevation 4500-5000 m, and inferior distribution in other elevations.

Built-up land was only distributed in elevation 0-5000 m, and there was no built-up land when elevation >5000 m. Moreover, the topographic distribution index of built-up land with an elevation of 2000-2500 m in 1980 and 1990 exceeded 20. However, the topographic distribution index of built-up land in this elevation level decreased gradually from 1980 to 2015, the lowest index was still 14.8179 in 2015. It could be seen that the distribution advantage of built-up land in elevation 2000-2500 m was obvious. In addition, built-up land also had a distribution advantage in elevation 0-2000 m and 2500-4000 m. This indicated that human built-up land was mainly distributed in the low-elevation region, the region with the most frequent human activities, human urban, rural, industrial, mining, and residential land was mainly distributed in low-elevation areas. With the increase of elevation, the topographic distribution index of built-up land gradually decreased until it was no longer suitable for human construction when elevation was >5000 m. From then on, there was no built-up land distribution.

The distribution of cropland was similar to that of built-up land, and elevation 0-4000 m was the dominant distribution. The topographic distribution index gradually decreased since the elevation was 2000-2500 m, there was no cropland distribution over 6000 m, and the topographic distribution index was extensive in elevation 0-2500 m. For example, in 2015, the cropland topographic distribution index in elevation 0-2000 m was 11.2109, in elevation 2000-2500 m was 15.2638, indicating an obvious distribution advantage.

Forest had a distribution advantage in elevation 0-4500 m. In addition, the topographic distribution index of forest in elevation 0-2000 m was the largest. For example, in 2015, the topographic distribution index of forest in elevation 0-2000 m was 6.885, significantly higher than other elevation gradients. From 1980 to 2015, the topographic distribution index of forest in elevation 2000-2500 m gradually decreased. Water body had a distribution advantage only in elevation 4500-5000 m and >5500 m, of which the topographic distribution index of water body area with an elevation >5500 m was high, mainly because a large number of lands in these two elevation areas were covered by

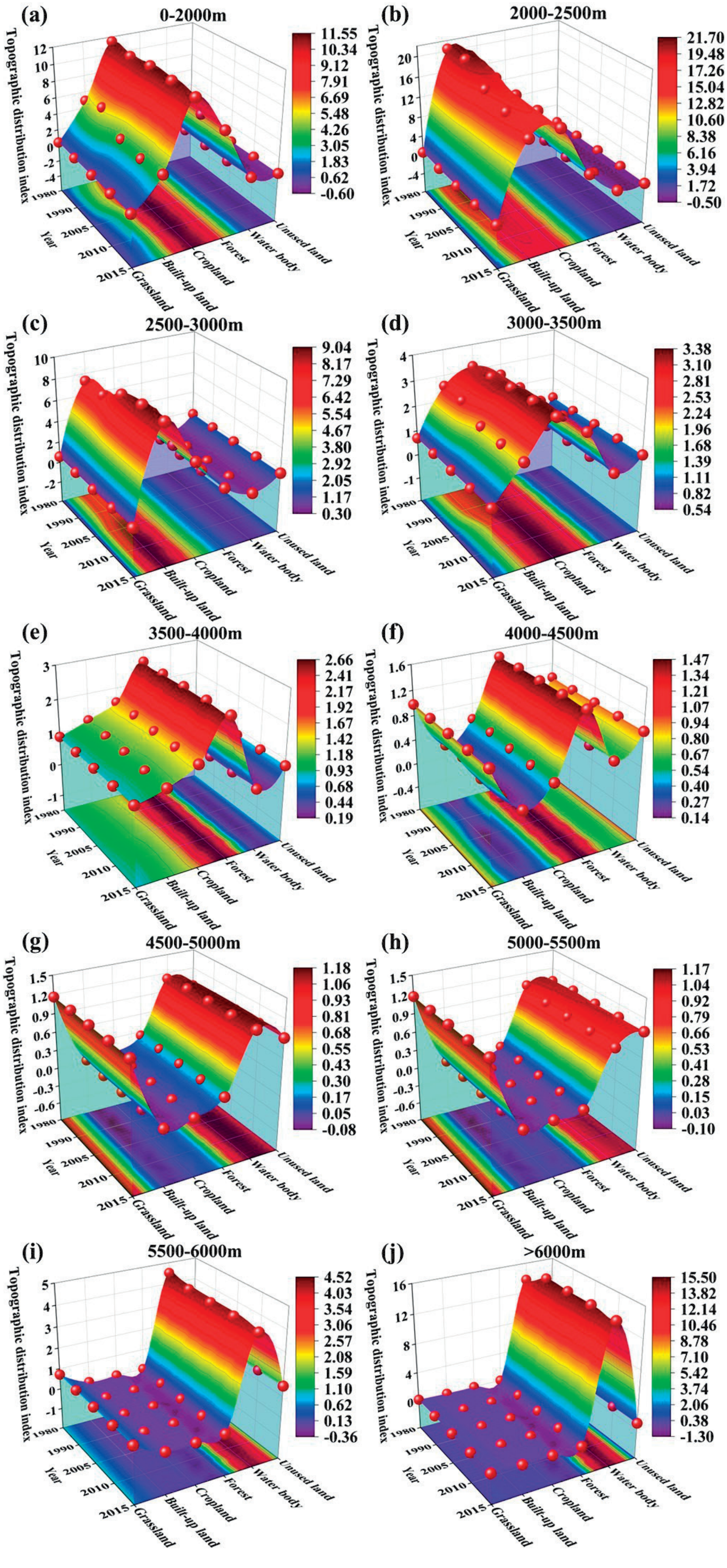

Fig. 3. The topographic distribution index of different elevation levels in the Qinghai-Tibet Plateau: a) 0-2000 m; b) 2000-2500 m; c) 2500-3000 m; d) 3000-3500 m; e) 3500-4000 m; f) 4000-4500 m; g) 4500-5000 m; h) 5000-5500 m; i) 5500-6000 m; j) >6000 m.

glaciers and snow throughout the year, that was, there were many permanent glaciers and snow. In addition, the topographic distribution index of water body area in elevation 2000-3000 m gradually increased from 1980 to 2015. Unused land had a distribution advantage in elevation 2500-3500 m and 5500-6000 m.

Slope Gradient Effect of Land Use

It could be seen from Fig. 4 that the distribution of various land use types in the QTP varied greatly in slope gradient. From 1980 to 2015, grassland had a distribution advantage in slope 2-10°. With increasing slope gradient, the topographic distribution index of grassland increased first and then decreased, and the topographic distribution index of grassland was the largest in slope 2-4°.

From 1980 to 2015, the topographic distribution index of built-up land showed a decreasing trend with the increase of slope. The topographic distribution index of built-up land was the largest in slope 0-2°, and the dominant distribution interval was mainly concentrated in the gradient with lower slope, indicating that human daily production and life were mainly concentrated in the area with lower slope, and the area with higher slope was not conducive to daily human life. In addition, the topographic distribution index in slope 0-2° increased gradually from 1980 to 2015, and in contrast, the topographic distribution index in slope 2-10° decreased gradually from 1980 to 2015, indicating that built-up land gradually shifted to land with the lower slope with the increase of years. There was little difference in the topographic distribution index of cropland in each slope gradient because cropland was mainly distributed in the region with a low slope. However, the area with a low slope was also large in the QTP, so there was little difference in the topographic distribution index of cropland in each slope gradient. From 1980 to 2015, the forest topographic distribution index of the QTP did not change significantly with the years but had a significant slope gradient effect. With the increase of slope, the topographic distribution index of forest increased gradually, and presented dominant distribution when the slope >10°. When the slope was >35°, the topographic distribution index reached the maximum. From 1980 to 2015, it was >5, indicating an obvious distribution advantage. Water body had a distribution advantage in slope 0-2° and >20°. Unused land had a distribution advantage only in slope 0-2°.

Aspect Gradient Effect of Land Use

It could be seen from Table 1 that grassland had a distribution advantage only on sunny slope. Built-up land had a distribution advantage on flat slope, semi-shady slope, and sunny slope. The topographic distribution index of built-up land on flat slope was significantly higher than that on other aspects. For example, it was 12.9833 in 2015, indicating that the distribution advantage of built-up land on flat slope was noticeable and flat slope was suitable for daily production and life of human beings. Cropland had a distribution advantage on semi-shady slope, and sunny slope, indicating that semi-shady slope and sunny slope had strong solar radiation and were suitable for the growth of crops. In addition, from 1980 to 2015, the topographic distribution index of cropland on semi-shady slope decreased gradually, while that on semi-sunny slope increased gradually, indicating that the cropland in the QTP had a trend of shifting from semi-shady slope to semi-sunny slope.

Forest had a distribution advantage on shady slope, semi-shady slope, and semi-sunny slope. Water body had a distribution advantage on flat slope, shady slope, and semi-shady slope. The topographic distribution index of water body on flat slope was significantly higher than that on other aspects, for example, 7.3128 in 2015, indicating an obvious distribution advantage, reflecting that flat slope, shady slope, and semi-shady slope are suitable for natural land area, water conservancy facilities land, permanent glacier and snow distribution. In addition, the topographic distribution index of water body on flat slope and shady slope from 1980 to 2015 increased gradually, indicating that the government had achieved success in water conservation in recent years. Unused land had a distribution advantage on flat slope, shady slope, and sunny slope. In addition, the topographic distribution index of unused land on flat slope and shady slope increased gradually from 1980 to 2015, while the topographic distribution index on semi-shady slope and sunny slope decreased gradually.

Terrain Niche Index Gradient Effect of Land Use

The TNI was calculated based on formula (1) (Fig. 5), and its value ranged from 0.15 to 3.19, with an average value of 1.29. It was analyzed according to the Natural Breaks (Jenks), divided into 0-0.59, 0.59-0.84, 0.84-1.06, 1.06-1.37, 1.37-1.68, 1.68-1.93, 1.93-2.15, 2.15-2.34, 2.34-2.51, >2.51, 10 levels in total. The corresponding proportions were 3.386%, 14.237%, 19.158%, 22.031%, 19.453%, 12.258%, 6.570%, 2.349%, 0.493% and 0.066%. The area with TNI 1.06-1.37 was the largest, and the area with TNI>2.51 was the smallest. The TNI of Yunnan ranged from 0.31 to 2.87, with an average of 1.64; the TNI of Sichuan province ranged from 0.33 to 2.72, with an average of 1.53; the TNI of Xinjiang ranged from 0.40 to 3.18 with an average of 1.34; the TNI of Qinghai ranged from 0.37 to 2.63 with an average of 1.07; the TNI of Gansu province ranged from 0.34 to 2.70, with an average of 1.23; the TNI of Tibet ranged from 0.15 to 3.19, with an average of 1.35. Tibet had the largest range of TNI, while Yunnan had the largest mean value.

As can be seen from Fig. 6, with the increase of TNI, the topographic distribution index of grassland first increased and then decreased, and grassland had

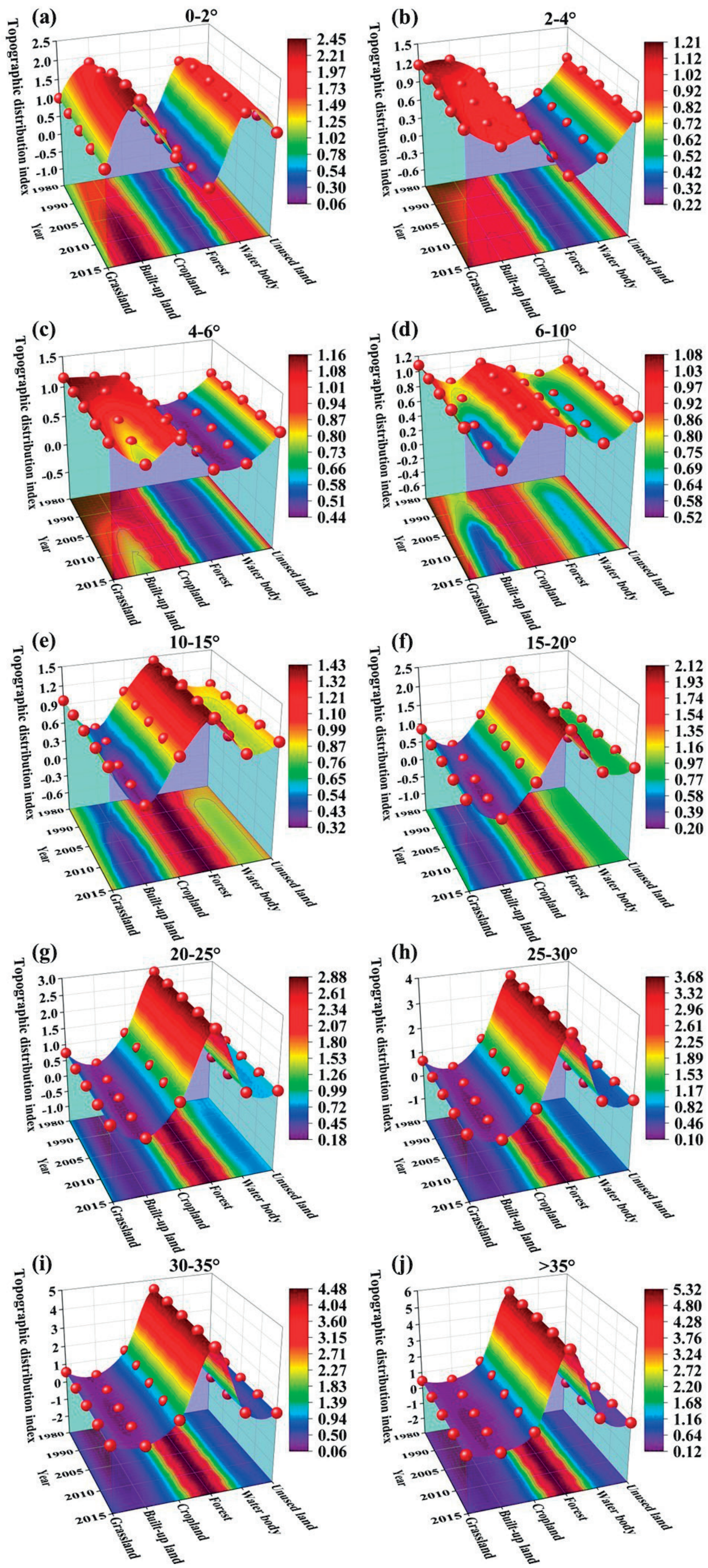

Fig. 4. The topographic distribution index of different slope levels in the Qinghai-Tibet Plateau: a) 0-2°; b) 2-4°; c) 4-6°; d) 6-10°; e) 10-15°; f) 15-20°; g) 20-25°; h) 25°-30°; i) 30-35°; j) >35°.

Table 1. The topographic distribution index of different aspect levels in the Qinghai-Tibet Plateau.

Year	Aspect	Grassland	Built-up land	Cropland	Forest	Water body	Unused land
1980	Flat	0.5841	7.1729	0.5669	0.0703	5.8265	1.371
	Shady	0.9859	0.9069	0.8768	1.0313	1.0369	1.0143
	Semi-shady	0.9983	1.2022	1.1746	1.0487	1.113	0.9558
	Sunny	1.0246	1.1382	1.1045	0.7984	0.8829	1.0328
	Semi-sunny	0.9903	0.7355	0.8301	1.1121	0.9467	0.9945
1990	Flat	0.6012	4.2121	0.3882	0.0548	6.5342	1.3412
	Shady	0.9863	1.0031	0.949	1.0419	1.0475	1.0063
	Semi-shady	0.9989	1.1654	1.1651	1.0428	1.1131	0.9606
	Sunny	1.0237	1.0805	1.0268	0.7833	0.8799	1.0394
	Semi-sunny	0.9903	0.7365	0.8372	1.1225	0.9362	0.9911
2005	Flat	0.5807	10.3786	0.5771	0.0699	6.9468	1.2906
	Shady	0.9876	0.9722	0.9368	1.0441	1.0497	1.0031
	Semi-shady	0.9988	1.1637	1.1302	1.0359	1.1058	0.9649
	Sunny	1.023	1.0362	1.0562	0.7821	0.8816	1.0401
	Semi-sunny	0.9906	0.8023	0.8522	1.1249	0.9371	0.9895
2010	Flat	0.5779	11.923	0.5767	0.0698	7.0476	1.2717
	Shady	0.9875	0.9701	0.9368	1.0444	1.0504	1.0029
	Semi-shady	0.9988	1.1452	1.1275	1.0359	1.1055	0.965
	Sunny	1.023	1.0409	1.0578	0.782	0.8814	1.0403
	Semi-sunny	0.9906	0.8175	0.8533	1.1248	0.9368	0.9895
2015	Flat	0.5634	12.9833	0.5808	0.0673	7.3128	1.2318
	Shady	0.9874	1.0182	0.9372	1.0443	1.0537	1.0024
	Semi-shady	0.9987	1.1457	1.1242	1.0359	1.1053	0.9651
	Sunny	1.0232	1.0079	1.0595	0.782	0.8797	1.0406
	Semi-sunny	0.9908	0.7982	0.8546	1.1249	0.935	0.9897

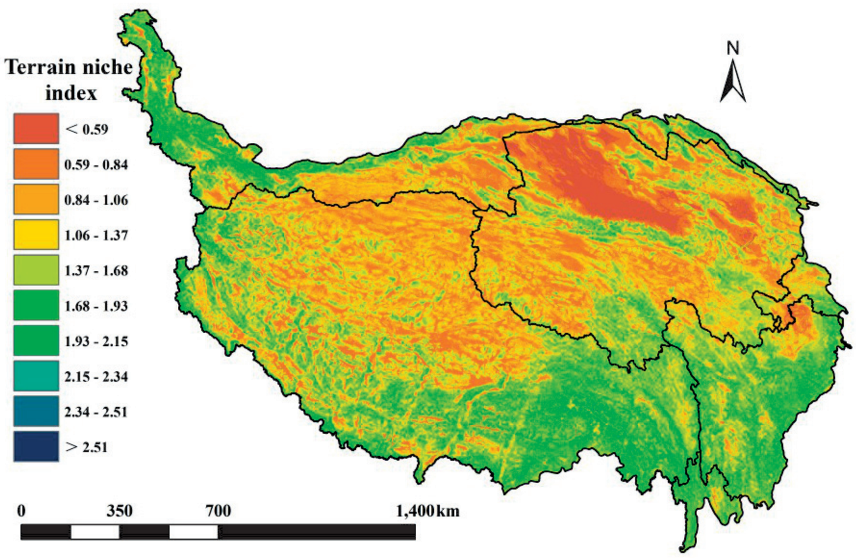

Fig. 5. The terrain niche index of the Qinghai-Tibet Plateau.

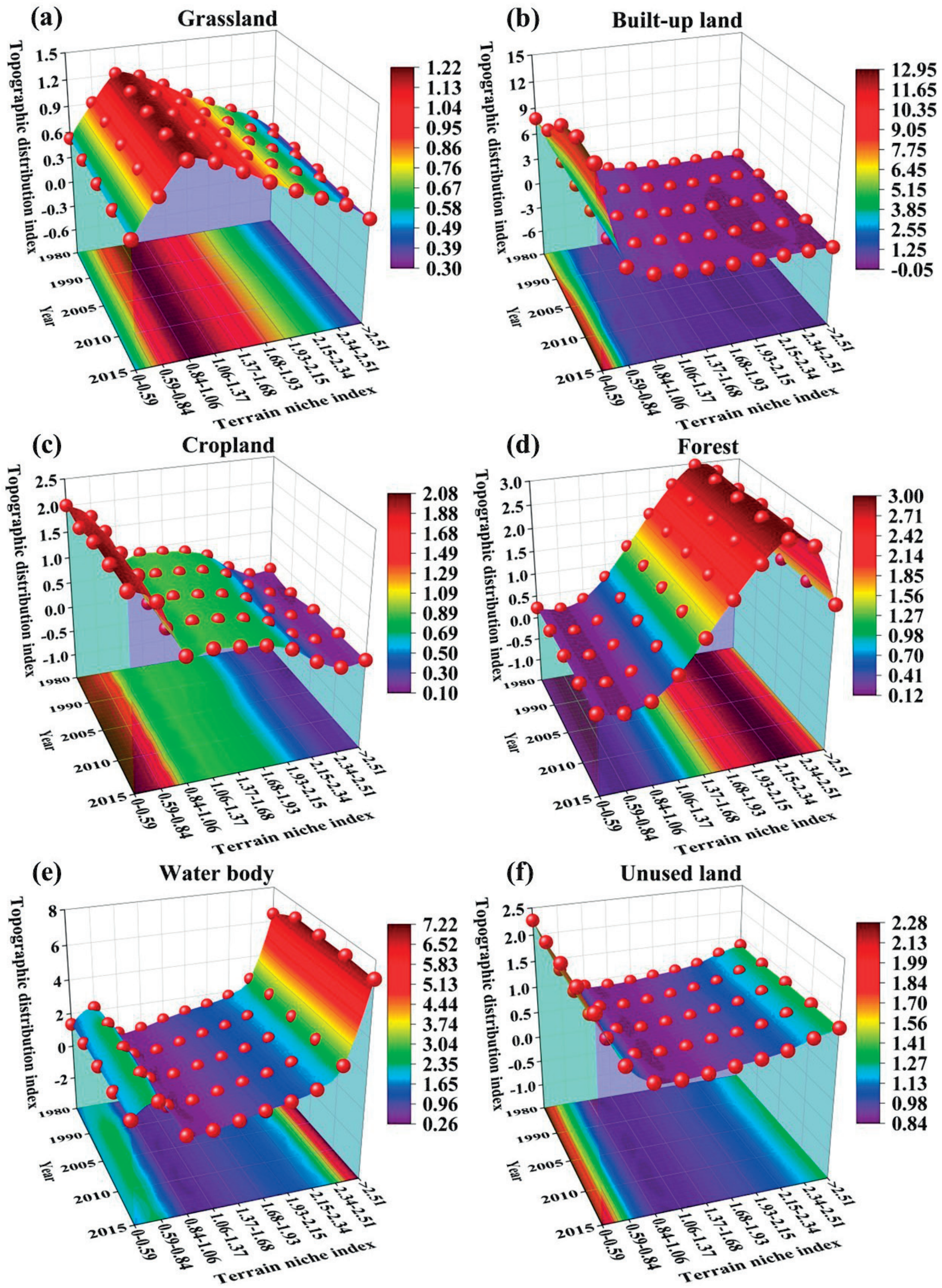

Fig. 6. The topographic distribution index of different terrain niche index levels in the Qinghai-Tibet Plateau: a) Grassland; b) Built-up land; c) Cropland; d) Forest; e) Water body; f) Unused land.

a distribution advantage in the region with TNI 0.84-1.68. The change of grassland topographic distribution index from 1980 to 2015 was small, which proved that the grassland distribution was in a relatively balanced state.

The topographic distribution index of built-up land showed a trend of decreasing with the increase of TNI. Built-up land had a distribution advantage in areas with TNI <0.84, and then the topographic distribution index gradually decreased. In 1980 and 1990, the topographic distribution index of the area with TNI>2.51 was 0, reflecting that the built-up land area in the terrain was 0. The topographic distribution index of built-up land in areas where the terrain index <0.59 was large, and the distribution advantage was obvious, indicating that the low TNI area was very suitable for human daily production and life. The topographic distribution index of the area with TNI <0.59 increased from 7.7947 in 1980 to 12.7597 in 2015, while the topographic distribution index of the area with TNI 0.59-1.68

decreased obviously, indicating that the built-up land had a trend of gradually shifting to the area with low TNI. Cropland only had a distribution advantage in areas with a topographic level index <0.84, indicating that areas with low topographic levels are suitable for crop growth.

Forest had a distribution advantage in the area with TNI>1.37, indicating that the area with higher TNI was suitable for forest distribution. The topographic distribution index of forest changed little from 1980 to 2015, which proved that the distribution of forest was in a relatively balanced state. Water body had a distribution advantage in the region with TNI<0.84 and >1.93, and water body had a higher topographic distribution index in the region with TNI>2.51, and the distribution advantage was obvious, mainly because the permanent glacier and snow were mostly distributed in the high TNI. In 2015, compared with 1980, the regional topographic distribution index of water body in TNI 1.06-2.34 decreased, and the topographic distribution index at other TNI increased. With the increase of TNI, the topographic distribution index of unused land decreased first and then increased, and the area with TNI <0.84 and >2.15 had a distribution advantage.

Topographic Relief Gradient Effect of Land Use

Using the mean change point analysis method, by Python and Origin 2019b software, we calculated that the curve had the largest value at the 11th point, the corresponding grid window size was 12×12 pixels, and the optimal window area was 31.4841 km^2.

Based on DEM data, the TR of the QTP was extracted under a window with a size of 12×12 pixels (Fig. 7). The TR of the study area ranged from 2 to 6632 m, with an average of 661.99 m. Hui et al. divided TR into six levels [26]. Basing on their classification criteria and combining with the actual situation of the study area, we divided TR into five levels: extremely small relief (0-70 m), small relief (70-200 m), medium relief (200-500 m), high relief (500-1000 m), and extremely high relief (>1000 m). The corresponding proportions were 5.716%, 12.780%, 26.976%, 32.473%, and 22.056%, in which the high relief area was the largest and the extremely small relief area was the smallest. The range of TR in Xinjiang was 6-6421 m, with an average of 766.53 m. The range of TR in Qinghai was 2-2825 m, with an average of 411.81 m. The range of TR in Gansu was 7-3772 m, with an average value of 695.02 m. The range of TR in Tibet was 4-6632 m, with an average of 677.18 m. The range of TR in Sichuan was 6-3591 m, with an average of 1029.57 m. The range of TR in Yunnan was 155-4154 m, with an average of 1446.33 m. Tibet had the largest range of TR, and Yunnan had the largest average TR.

As can be seen from Fig. 8, grassland had a distribution advantage in areas with small, medium, and high reliefs. Overall, the topographic distribution index curve showed a trend of large in the middle and small on both sides, indicating that the medium relief range was suitable for grassland distribution.

The topographic distribution index of built-up land was the largest in the area with extremely small relief and the distribution advantage was evident, while the topographic distribution index was the smallest in the area with extremely high relief, indicating that the relief was too large for human daily production and life. In 2015, compared with 1980, the topographic distribution index of built-up land increased in the area with extremely small relief, and decreased in the area with medium relief and high relief, indicating that built-up land had a trend of shifting to the area with lower relief in the past 35 years.

The topographic distribution index of forest was dominant only in the area with extremely high relief, indicating that the area with higher relief was suitable for forest distribution, and the topographic distribution

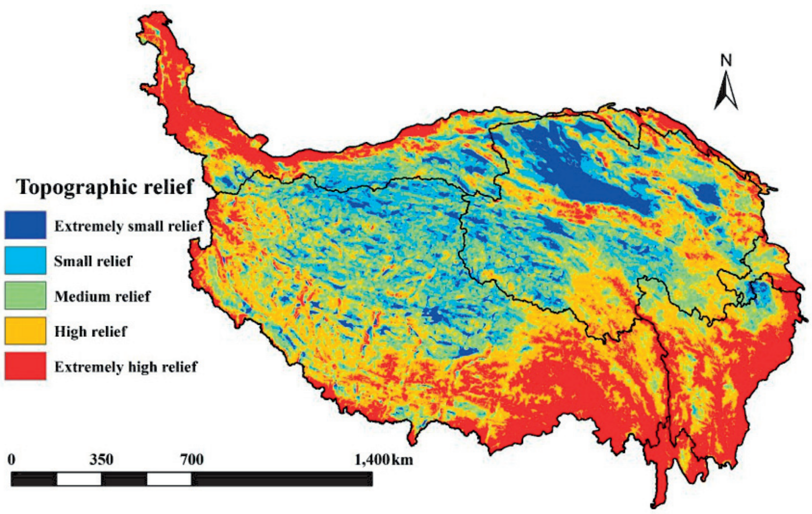

Fig. 7. The topographic relief of the Qinghai-Tibet Plateau.

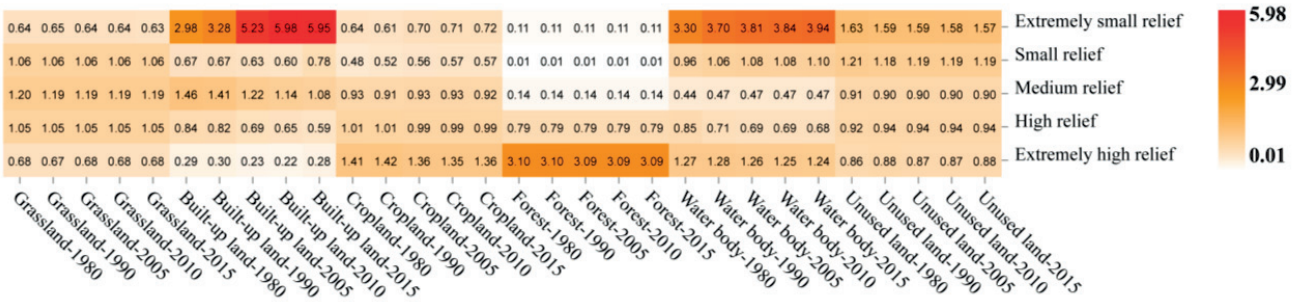

Fig. 8. The topographic distribution index of different topographic relief levels in the Qinghai-Tibet Plateau.

index of forest had little change in each stage. Water body had the advantage of distribution in the interval of extremely small relief and extremely high relief. Overall, the topographic distribution index curve showed a trend of small in the middle and large on both sides, indicating that the areas with medium relief were not suitable for water body distribution. The main reason was that natural land water body and water conservancy facilities were mainly distributed in river valleys with low TR, and permanent glaciers and snow were mainly distributed in high mountain areas with high TR. In addition, from 1980 to 2015, the topographic distribution index of water body increased gradually in the area of extremely small relief, and decreased gradually in the area of high relief, indicating that the distribution of water body had a trend of shifting to the area of lower relief.

Unused land had a distribution advantage in the areas with extremely small relief and small relief, indicating that the regions with lower relief were suitable for unused land distribution. From 1980 to 2015, the topographic distribution index of unused land gradually decreased in the areas with extremely small relief and gradually increased in the areas with high relief, indicating that unused land had a trend of transferring to the regions with more considerable fluctuation.

Analysis of the Comprehensive Index of Land Use Degree in Different Terrain Gradients

The region with lower elevation and higher slope had the highest comprehensive index of land use degree. As a result, the area with medium TNI had the highest comprehensive index of land use degree. The main reason was that the proportion of unused land in the region with higher slope was relatively small, and the proportion of unused land in the region with lower elevation was small. It was suitable for the distribution of cropland and built-up land. For example, in 2015, unused land accounted for 16.75% of the area in slope >35°, and 31.56% of the area in slope 0-2°. In 2015, the proportion of unused land in 0-2000 m elevation was 0.47%, cropland was 8.04%, built-up land was 0.34%. However, the proportion of unused land in elevation >6000 m was 23.21%, and there was no distribution of cropland and built-up land in this elevation.

The comprehensive index of land use degree of flat slope was the lowest, and there was little difference among other aspects. The main reason was that the grassland and forest area of flat slope was relatively small, and the unused land was relatively high. Overall, the comprehensive index of land use degree of flat slope showed an upward trend from 1980 to 2015, mainly because the area of built-up land and water body increased while the area of unused land decreased, indicating that economic development and population growth increased people's demand for built-up land, and water body increased due to water conservancy facilities built by the government.

The comprehensive index of land use degree in extremely small relief was significantly smaller than other TR, mainly due to the large proportion of unused land area. For example, in 2015, unused land in extremely small relief area accounted for 41.09%, while unused land area in medium relief area accounted for 23.61%. Overall, compared with 1980, the comprehensive index of land use degree in the area with extremely small relief increased in 2015, mainly due to the increase of built-up land, cropland, water body, and the decrease of unused land area.

Discussion

Different terrain gradients of the QTP had different impacts on land use. Combined with the actual conditions of the study area, the main driving factors of land use were natural and human factors.

Natural Factors

Elevation, slope, aspect, TNI, and TR directly affected the land use changes in the study area. The study area was sparsely populated and had a harsh natural environment. The slope was mainly 0-15°, and the elevation was mainly 4000-5500 m. The TR was mainly medium relief, high relief, and extremely high relief, which also determined that the study area was mainly grassland and unused land, and there were few cropland and built-up land. Cropland and built-up land were mainly distributed in Yarlung Zangbo River Valley and Hehuang Valley, mainly because the water was the condition of crop irrigation, and crops had high requirements on temperature, heat in the valley was not easy to disperse, crops were easier to survive, but also suitable for human daily production and life. This area had low elevation, low slope, and small TNI, mostly flat slope and sunny slope. The study area was rich in water resources and was known as the "Water tower of Asia". Water body was mainly composed of glaciers with considerable reserves and a large number of lakes. Glaciers were mainly distributed in high elevation, large slope, shady and semi-shady slope, large TNI, and extremely high relief. In contrast, lakes were mainly distributed in areas with large elevation, small slope, flat slope and shady slope, extremely small relief. Forest in the study area was mainly distributed in the southeastern and eastern alpine valley areas, such as southeast Tibet, west Sichuan, and northwest Yunnan. This area had large slope, medium or high TNI, high TR, and little disturbance by human activities, so it was suitable for forest distribution.

Precipitation and temperature were also significant factors affecting land use. By analyzing variations in annual accumulated precipitation and mean annual temperature in the QTP from 2000 to 2015, both temperature and precipitation were found to have fluctuated. Temperature increased at a mean rate of 0.025°C/a. Precipitation increased at a mean rate of 0.134 mm/a. The climate was generally warmer and more humid, providing favorable conditions for vegetation growth and snow melting, which was likely the main reason for the gradual increase in grassland and water body. The area of grassland increased by 2723 km^2 from 1990 to 2015 and relevant studies showed that the area of most lakes in the QTP increased from 1995 to 2015 [30].

Human Factors

The land use in the QTP was not only affected by natural factors, but also by human factors. In terms of population, for example, according to the China Statistical Yearbook data from the National Bureau of Statistics (http://www.stats.gov.cn/), the population of Tibet increased from 239.84×10^4 people in 1995 to 323.97×10^4 people in 2015, and the population of Qinghai increased from 392.79×10^4 people in 1982 to 588.43×10^4 people in 2015. As a result, the area of built-up land in the study area increased gradually. From 1980 to 2015, the topographic distribution index in slope 0-2° increased from 1.8404 to 2.4482. The topographic distribution index of the region in slope 2-10° decreased gradually. The topographic distribution index of the region with TNI <0.59 increased from 7.7947 in 1980 to 12.7597 in 2015, while the topographic distribution index of the region with TNI 0.59-1.68 decreased significantly. The topographic distribution index of the region with extremely small relief increased from 2.9757 in 1980 to 5.95 in 2015, while the topographic distribution index of the region with medium relief and high relief decreased gradually. It could be seen that in the past 35 years, the land use types in the study area tended to shift to areas more suitable for human habitation, such as areas with smaller slope, lower TNI and relief.

The number of livestock in the study area reached the highest in 1980 and had been maintained at around 2300×10^4, which is far beyond the normal carrying range, leading to the continuous degradation of the grassland [31].

In terms of policy, Qinghai province was taken as an example. In 2000, the western development strategy was implemented, and infrastructure construction was intensified. By 2010, a road network "two horizontal roads, three vertical roads and three vertical roads" was basically completed. In 2006, the opening of the Qinghai-Tibet Railway significantly increased the GDP of the regions along the line [32], the tourism industry achieved leap-forward growth, the industrialization process accelerated, and the economic construction made remarkable achievements. As a result, the demand for built-up land keeps increasing, which showed that the area of built-up land increased gradually. The Chinese government had also adopted policies to protect the ecological environment of research areas and realized the rational utilization and sustainable development of land resources [33]. The implementation of the above policies affected the land use change in the QTP.

Living habits and production methods were also significant factors. Herdsmen mainly live a semi nomadic lifestyle. In the 1970s, the herdsman settlement project was implemented, and grazing mode changed from semi nomadic to settled grazing. Settled herdsmen began to build fences, buy feed, plant grass manually or rent grassland, which enhanced the adaptability of herdsmen to the ecological environment and reduced the ecological pressure. In recent years, by promoting the centralized management of cooperatives and introducing advanced technologies, the production efficiency of pastoral areas had greatly improved, the ecological balance was protected, and the degradation of grassland had reduced.

Conclusions

Based on mean change point analysis, we had calculated the optimal calculation window size for TR in the QTP was 31.4841 km^2. Combining multiple terrain factors such as TR, aspect or TNI could better analyze the impact of terrain on land use. Driven by natural and human factors, the terrain gradient effect of land use in the QTP was significant. The degree of land use in low terrain gradient was enhanced. The change of land use was relatively stable on the middle-high terrain gradient. However, while focusing on the development of low terrain gradient, it is necessary to pay attention to the regional ecological environment. In the future, the government should consider the terrain gradient effect of land use, issue relevant policies, focus on ecological protection, and strengthen the scientific planning and rational distribution of land use.

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Conflict of Interest

The authors declare no conflict of interest.

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