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Land Use Simulation and Landscape Ecological Risk Assessment on the Qinghai-Tibet Plateau

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Abstract: The land use and land cover pattern of the Qinghai-Tibet Plateau (QTP) is an important basis for the structure and function of the QTP ecological barrier. It is of great significance to simulate the land use pattern and landscape ecological risk of the QTP under future scenarios for the construction of the QTP barrier area and to promote the sustainable use of land resources. The QTP was selected as the study area. Based on the spatial pattern of land use in 2010 and 2020, the PLUS model was used to predict the land use patterns of the QTP in 2030 under the two scenarios of natural development and ecological conservation. The landscape ecological risk index was constructed to evaluate the past, present, and future landscape ecological risk of the QTP. The natural break point method was used to divide the landscape ecological risk index into five levels: lower ecological risk, low ecological risk, medium ecological risk, high ecological risk, and higher ecological risk. The results showed that: (1) Under the natural development scenario, the area of cropland, forestland, grassland, and unused land decreased continuously, while the areas of water and built-up land increased gradually. Under the ecological conservation scenario, the areas of forestland and grassland increased by 130 km^2 and 2293 km^2, respectively, compared with the natural development scenario. (2) Under the natural development scenario, the overall ecological risk of the QTP increased from 2010 to 2030, which showed that the proportions of lower ecological risk area decreased, while the proportion of medium and high ecological risk area increased. Under the ecological conservation scenario, compared with the natural development scenario, the area of lower, low, and high ecological risk increased by 4044 km^2, 2484 km^2, and 6401 km^2, respectively, while the areas of medium and higher ecological risk decreased by 6333 km^2 and 6597 km^2, respectively.

Keywords: Qinghai-Tibet Plateau; land use simulation; future scenarios; landscape ecological risk

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1. Introduction

The Qinghai-Tibet Plateau (QTP) is known as the "roof of the world" and the "world's third pole" [1]. Its unique geographical location and rich natural resources make it an ecological security barrier for China and even Asia, meaning it plays an important role in ecological conservation [2]. However, the QTP's ecosystem is fragile and its natural environment is complex [3]. Under the combined influence of human and natural factors, the LUCC, which form an important basis for supporting the structure and function of the QTP ecological barrier, is prone to change. Such change significantly impacts the QTP's internal ecological environment and its development, thus affecting the whole world [4].

An important topic in ecological risk assessment at the regional scale, landscape ecological risk refers to the possible adverse consequences of the interaction between landscape patterns and ecological processes under the influence of natural or human factors [5]. It affects the intensity of regional ecological risk, and then causes natural disasters [6–8]. With the development of computer technology, the models used for land use simulation are developing apace. In CLUE-S, FLUS, and PLUS models [9–11], for example, the accuracy of land use model simulation is constantly improving. Therefore, researchers have begun to assess regional ecological risk status from the perspective of landscape ecology by land use pattern [12]. This plays an important role in determining the overall characteristics and trends of change of regional ecological risk and in carrying out ecological risk management.

At present, research on land use change in the QTP mainly focus on densely populated areas and climate sensitive areas. Such areas include the Yellow River-Huangshui River Valley, the "One River and Two Rivers Streams" area [13–17], the Northern Tibet Plateau, the Three-River Headwaters Region [18–22], and the Qomolangma National Nature Reserve [23–25]. Moreover, the land use types studied are specific, and there is a lack of systematic understanding of the LUCC process for the whole of the QTP. There is little research on land use simulation of the QTP. Most studies on the landscape ecological risk assessment of the QTP focus on small areas, such as cities, river basins, wetlands, and infrastructure construction areas [26–31]. Large-scale systematic landscape ecological risk assessment studies under current and future scenarios for the whole QTP are still lacking. Therefore, the simulation and assessment of land use change and ecological risk for the QTP have become important in the sustainable development and ecological conservation of the QTP. It is, therefore, crucial to better understand the overall characteristics and developmental trends of land use change and ecological risk on the QTP.

The QTP, therefore, was selected as the study area. Using land use data from the QTP for 2010 and 2020, the PLUS model was adopted to predict the land use under natural development and ecological conservation scenarios for 2030. The landscape ecological risk index was constructed to evaluate the overall landscape ecological risk characteristics of the QTP from 2010 to 2020 and different future scenarios for 2030. This study aims to promote the sustainable utilization of land resources on the QTP, to provide a reference for the construction of an ecological conservation barrier area and ecological civilization plateau and to provide a theoretical reference for the LUCC simulation and landscape ecological risk assessment of plateau regions across the world.

2. Materials and Methods

2.1. Study Area

The QTP covers an area of more than 250×10^4 km^2 in China, with an average altitude of more than 4200 m covering six regions (Figure 1): Tibet, Qinghai, Gansu, Sichuan, Yunnan, and Xinjiang [32]. The QTP has an average annual temperature of −6–20 °C and annual precipitation of 50–2000 mm [33]. It is the cradle of the great rivers: the Yangtze River, Yellow River, and Yarlung Zangbo River and is known as the "Asian Water Tower" [34]. The QTP has complex terrains, diverse landforms, and a large amount of frozen soil. The frozen soil area of the QTP is about 115.02×10^4 km^2, making the QTP rank first among all the frozen soil regions in the middle-latitude of the world [35].

2.2. Data Source

The 30 m land use data from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences were reclassified (Table 1), pruned, and resampled to produce land use data sets with a resolution of 1 km for the QTP in 2010 and 2020. The other data source is shown in Table 2.

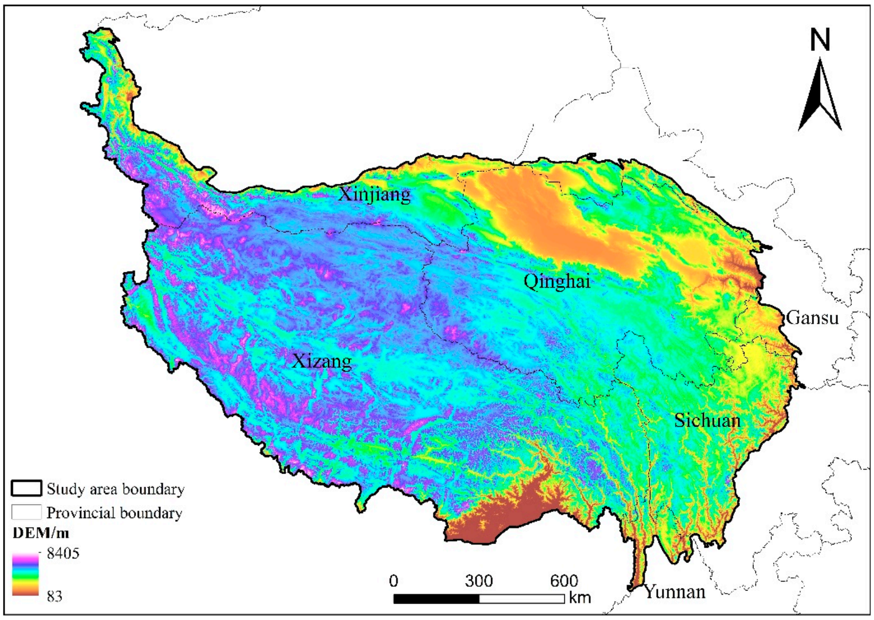

Figure 1. Location of the study area.

Table 1. Reclassification of land use types for the dataset.

Reclassification Number	Reclassification Name	Original Number	Original Description
1	Cropland	11	Paddy field
		12	Dry land
2	Forestland	21	Forestland
		22	Shrubland
		23	Sparse woodland
		24	Other woodlands
3	Grassland	31	High cover grassland
		32	Medium cover grassland
		33	Low cover grassland
4	Water	41	River and canals
		42	Lakes
		43	Reservoir pit
		44	Permanent glacial snow
5	Built-up land	51	Urban land
		52	Rural settlement
		53	Other construction land
6	Unused land	61	Sand
		62	Gobi
		63	Salt alkali soil
		64	Wetland
		65	Bare ground
		66	Bare rock stony ground
		67	Other

Table 2. Data source.

Data	Time	Resolution	Source
DEM	2010	1 km	Resource and Environment Science and Data Center https://www.resc.cn/ (accessed on 31 January 2023)
Temperature	2010, 2020	1 km	
Precipitation	2010, 2020	1 km	
Population density	2010, 2020	1 km	
GDP	2010, 2020	1 km	
Frozen soil	2010, 2020	1 km	National Qinghai Tibet Plateau Scientific Data Center https://data.tpdc.ac.cn/ (accessed on 31 January 2023)
QTP boundary	2019		National Geographic Information Resource Directory Service System https://www.webmap.cn/ (accessed on 31 January 2023)
Roads	2010		
Railway	2010		
Rivers	2010		
Lakes	2010		A Big Earth Data Platform for Three Poles http://poles.tpdc.ac.cn/ (accessed on 31 January 2023)

2.3. Methods

This study focused on the simulation of LUCC under future scenarios and assessed the ecological risk under different scenarios. The framework of this study was as follows: (1) Optimization of PLUS-model parameters. Continuously adjusting the model-run parameters using the two-phase LUCC and driver factors dataset to optimize the accuracy of the simulated LUCC and to obtain data such as land expansion, development potential, and optimal-run parameters. (2) Constructing future scenarios parameters. The land demands under the two scenarios were constructed using Markov chain models, transfer probability matrices, scenario states, and government planning policies. (3) Ecological risk assessment. The landscape ecological risk index was constructed to assess ecological risk.

The overall research framework of the study is shown in Figure 2.

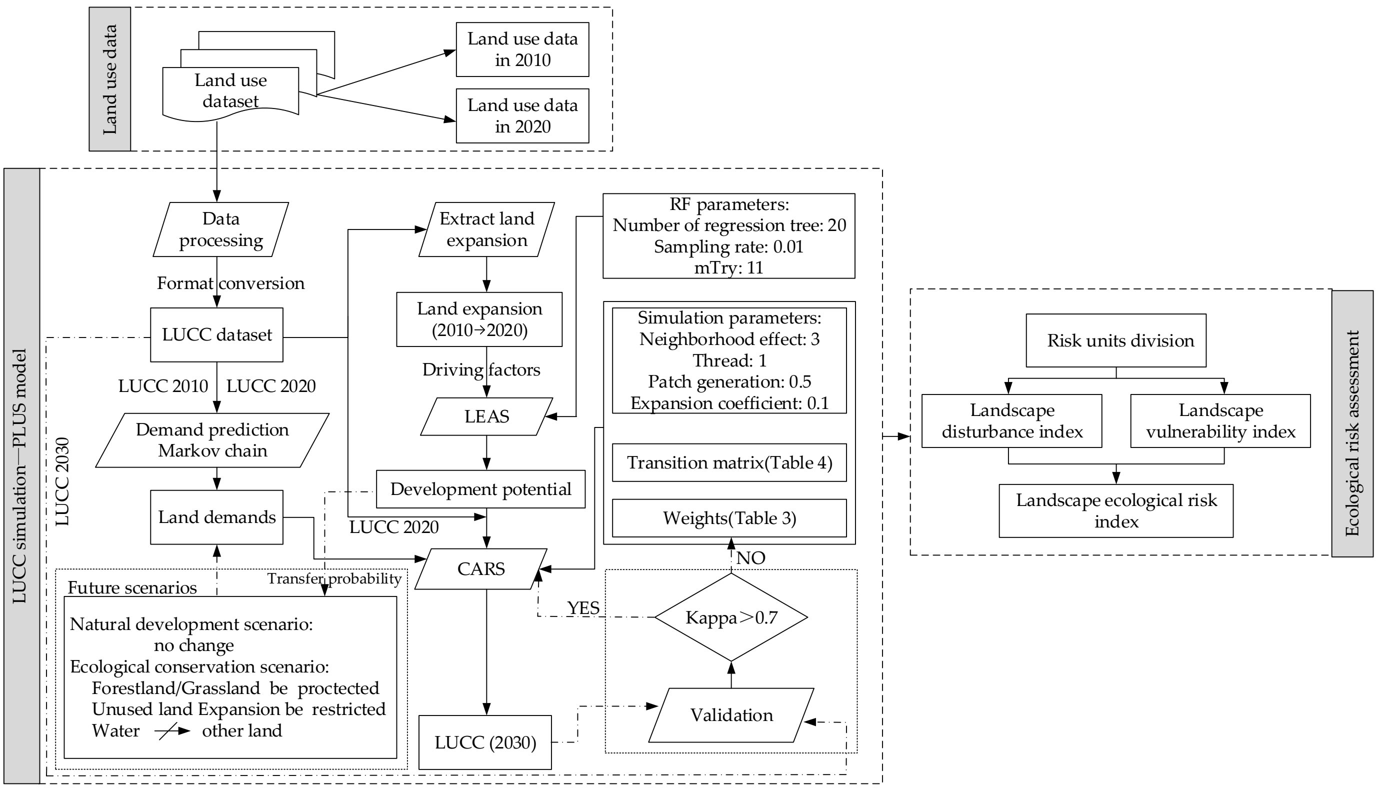

Figure 2. Research framework of this study.

2.3.1. Selection of Driving Factors

In recent years, the increasing intensity of human activities on the QTP combined with natural conditions, such as an uneven distribution of precipitation and a complex topography, has led to changes in regional land use types [36]. LUCC is the result of the interaction between humans and nature [37,38]. Based on existing research [39,40] combined with the actual situation of the study area, the driving factors of land use simulation were selected from the aspects of nature and socioeconomic; ArcGIS was used to make the driving factors dataset (Figure 3). All the driving factors were resampled into 1 km raster, and the number of rows and columns was 1982 and 2549, respectively. The projection was unified as Asia_Lambert_Conformal_Conic. As there is a large amount of frozen soil in the QTP, which is different from other regions in terms of driving factors selection, this study tested the rationality of the selection of frozen soil factors. With the participation of frozen soil, land use development potential is A. Then, according to the land use data of 2010 and the land use development potential A, the land use data C was simulated. Without the participation of frozen soil, land use development potential is B. Then, according to the land use data of 2010 and the land use development potential B, the land use data D was simulated. Finally, the actual land use data of 2020 and the simulated land use data C and D, for 2020, were tested using a Kappa test. When the sampling rate was 10%, the Kappa coefficient for land use data C was 0.995, which was higher than D. This indicates that the model simulation accuracy was higher when there was frozen soil in the driving factors.

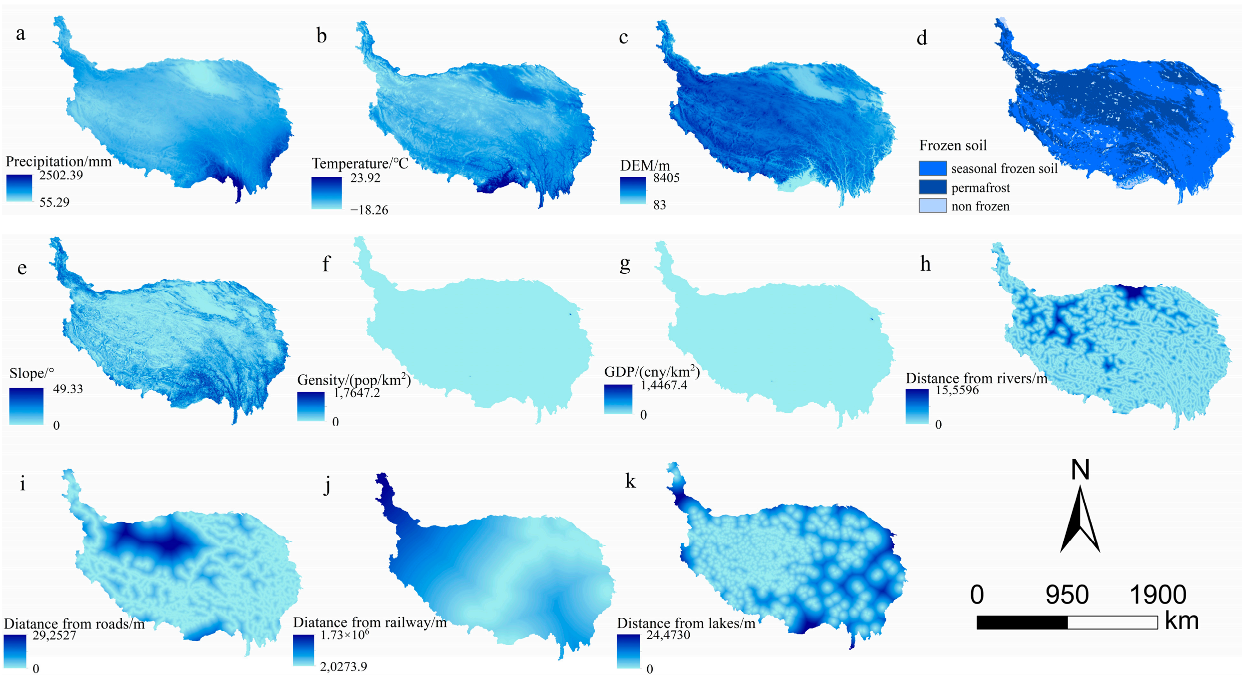

Figure 3. Driving factors for land use simulation (natural factors: (**a**) (precipitation), (**b**) (temperature), (**c**) (dem), (**d**) (frozen soil), (**e**) (slope); socioeconomic factors: (**f**) (population density), (**g**) (GDP), (**h**) (distance from rivers), (**i**) (distance from roads), (**j**) (distance from railway), (**k**) (distance from lakes)).

2.3.2. PLUS Model

The full name of the PLUS model is the patch-generating land use simulation model, which was developed by the Guan's group in 2021 [11]. The PLUS model, an improvement of the FLUS model, achieves higher simulation accuracy and better results than other land use simulation models [41]. The PLUS model mainly consists of two parts: land expansion analysis strategy (LEAS) and Cellular Automata acronym (CA) based on multiple random patch seeds (CARS) [11]. In this study, land demands for equal time intervals were first obtained in the Markov chain module using LUCC from 2010 to 2020. Secondly, we input

LUCC for 2010, development potential, conversion constrains, transition matrix, LUCC weights, and land demands and model parameters (Neighborhood Size, Patch generation, and Expansion coefficient) in the CARS module to simulate the LUCC for 2020. Then, the accuracy of Kappa was checked against the actual LUCC (10% of the sampling points were chosen for the Kappa test), the simulation parameters and LUCC weights were continuously adjusted to obtain the best results. The weights for cropland, forestland, grassland, water, built-up land, and unused land are shown in Table 3. Finally, we used the 2020 LUCC as the base year so that the model could be used to predict 2030 LUCC. The Kappa test is a method to verify the accuracy of model results, which can detect and analyze simulation results from both quantity and position. It is often used to measure the accuracy of prediction results [42]. For a sampling rate of 10%, the Kappa coefficient in this study is as high as 0.995, indicating that the PLUS model had extremely high applicability for the QTP. The PLUS model can be downloaded at https://github.com/HPSCIL.

Table 3. Weights of different land use type.

Land Use Type	Weight
Cropland	0.01
Forestland	0.01
Grassland	0.19
Water	0.42
Built-up land	0.07
Unused land	0.28

2.3.3. Future Scenarios Analysis

In this study, the natural development and ecological conservation scenarios were combined with the PLUS model to predict multiple scenarios for LUCC on the QTP in 2030. The natural development scenario is one in which the conversion rate of land use remains unchanged; moreover, the influence of various suitability factors on land use change remains consistent with before, and land use change occurs mainly due to the current socioeconomic development status and physical-geographical factors [43]. The ecological conservation scenario is a comprehensive and sustainable future land use change scenario. This scenario follows the principle of sustainable development and emphasizes coordinated development and conservation [44]; it is also an ideal scenario for future land use change on the QTP. Under the ecological conservation scenario forestland and grassland are protected, the transfer of forestland to grassland is prohibited, the expansion of unused land is restricted, and the transfer of water to other land is prohibited. The transition matrix under different scenarios is shown in Table 4.

Table 4. Land use transition matrix for different future scenarios in PLUS model.

Land Use	Natural Development Scenario						Ecological Conservation Scenario					
Type	CL	FL	GL	WA	BL	UL	CL	FL	GL	WA	BL	UL
CL	1	1	1	1	1	1	1	1	1	0	0	0
FL	1	1	1	1	1	1	0	1	0	0	0	0
GL	1	1	1	1	1	1	0	1	1	1	0	0
WA	1	1	1	1	1	1	0	0	0	1	0	0
BL	0	0	0	0	1	0	0	0	0	0	1	0
UL	1	1	1	1	1	1	1	1	1	1	1	1

CL, FL, GL, WA, BL, and UL represent cropland, forestland, grassland, water, built-up land, and unused land; 0 indicates that transition is not allowed, and 1 indicates that transition is allowed.

2.3.4. Landscape Ecological Risk Assessment

In this study, landscape ecological risk assessment for the QTP was realized by constructing the landscape ecological risk index. The landscape ecological risk index (ERI_k) of the QTP consists of the landscape disturbance index (E_i) and landscape vulnerability index (F_i). The landscape disturbance index includes the landscape fragmentation index (C_i), landscape separation index (S_i), and landscape dominance index (D_i). This study area was divided into 10 km × 10 km, comprising a total of approximately 25,000 risk units.

(1) Landscape disturbance index (E_i)

The landscape disturbance index was used to reflect the degree of external disturbance in the ecosystem represented by different land types on the QTP. The greater the disturbance, the greater the ecological risk [45,46].

(i) Landscape fragmentation index (C_i)

The landscape fragmentation index represents the process in which patches of each land cover type change from single continuous to complex discontinuous under natural or human disturbance. The greater the value, the lower the stability of the ecosystem of the corresponding land cover type [47]. The formula is:

$$C_i = \frac{N_i}{A_i} \tag{1}$$

N_i is the number of patches of land use type i; A_i is the area of land use type i.

(ii) Landscape separation index (S_i)

The landscape separation index represents the degree of separation of different patch distributions in a single land cover type. The larger the value, the more geographically dispersed and complex the distribution of the land cover type is [48]. The formula is:

$$S_i = \frac{\sqrt{N_i \times A}}{2A_i} \tag{2}$$

A is the area of risk assessment unit.

(iii) Landscape dominance index (D_i)

The landscape dominance index represents the extent to which the land cover structure is dominated by a certain type; it also reflects the influence of the land cover type on the formation and change of the landscape pattern. The larger the landscape dominance index, the higher the landscape ecological risk. The formula is:

$$D_i = (Q_i + M_i)/4 + L_i/2 \tag{3}$$

Q_i is the ratio between the number of risk assessment units and the total number of risk assessment units of land use type; i. M_i is the ratio of the number of patches of land use type i to the total number of patches in the evaluation unit. L_i is the ratio between the patch area of land use type i and the total area of evaluation unit, namely, the relative density of land use type i.

The weights of C_i, S_i, and D_i were, respectively 0.5, 0.3, and 0.2 [49–51], and the formula for the landscape disturbance index is as follows:

$$E_i = a \times C_i + b \times S_i + c \times D_i \tag{4}$$

(2) Landscape vulnerability index (F_i)

Landscape vulnerability refers to the vulnerability of internal structures of ecosystems represented by different landscapes; it reflects the resistance capacity of different landscape types to external disturbances [52]. According to research results of others [53,54], and the actual situation of the study area, the vulnerability of landscape types in the study area was divided into six levels, from high to low, as follows: for unused land, water, grassland, cropland, forestland, and built-up land the values from high to low were 6, 5, 4, 3, 2, 1. These values were normalized to obtain the F_i values of the landscape vulnerability index for each land use type: 0.28, 0.24, 0.19, 0.14, 0.10, and 0.05, respectively.

(3) Landscape ecological risk index (ERI_k)

The landscape disturbance index and landscape vulnerability index were used to calculate the landscape risk index, and the formula is as follows:

$$ERI_k = \sum_{i=1}^{n} \frac{A_i}{A}(E_i * F_i) \quad (5)$$

Semi-variogram fitting and Kriging interpolation method were used to process the data for 2010, 2020, and 2030 to obtain a spatial distribution map of landscape ecological risk.

3. Results

3.1. Land Use Spatiotemporal Change

As can be seen from Figure 4, there was no significant change in land use pattern for the entire QTP in 2010 or 2020, as well as in the natural development and ecological conservation scenarios of 2030. Cropland mainly existed in the northeastern margin of the QTP, One River, and Two Rivers Streams areas, forestland mainly existed in the southeast of the QTP, and grassland existed throughout the QTP. Water mainly existed in the western and northern part of the QTP. Unused land mainly existed in the western and southern part of the QTP. However, the land use transition matrix (Table 5) showed that, from 2010 to 2020, the largest areas of unused land and grassland converted to water were 3581 km^2 and 1827 km^2, respectively, while the largest areas of cropland, grassland, and unused land converted into built-up land were 223 km^2, 349 km^2, and 242 km^2, respectively. Analysis from another perspective; a total of 5628 km^2 of other land were converted to water. The areas were 939 km^2 and 848 km^2 of other land which were converted to built-up land and unused land, respectively. The main characteristics of land use type transfer from 2010 to 2020 were grassland and unused land converted to water, cropland, grassland, and unused land converted to built-up land.

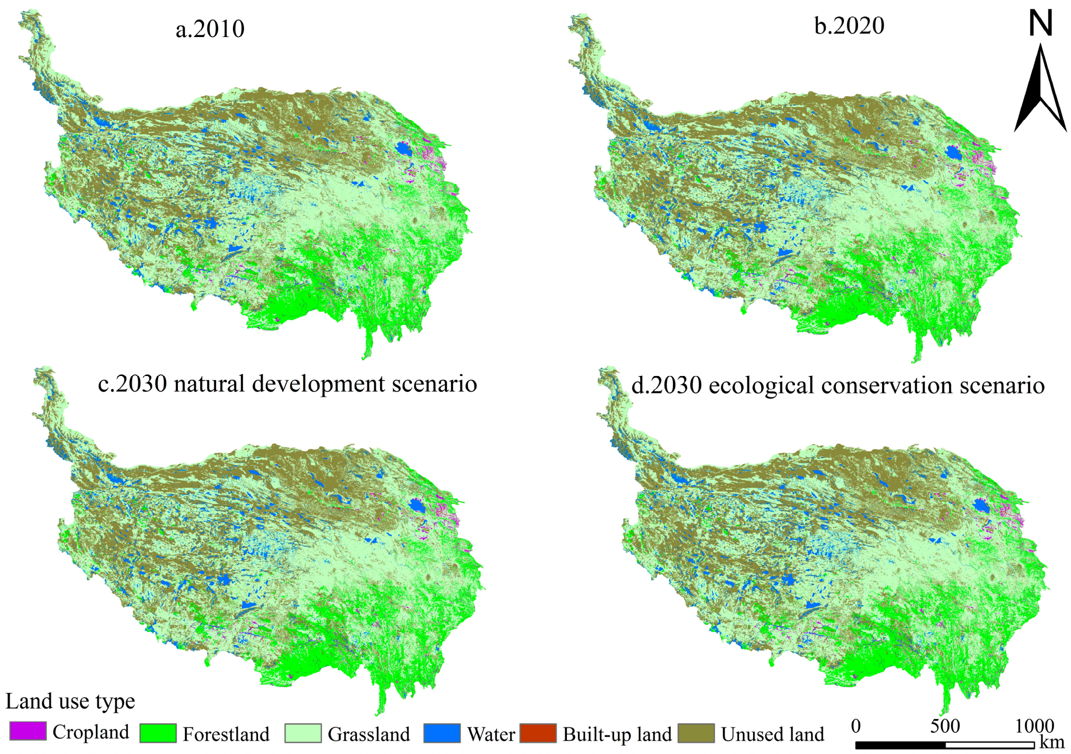

Figure 4. Spatial pattern of each land use type in the QTP from 2010 to 2030.

Table 5. Land use transition matrix from 2010 to 2020.

2010	2020					
	Cropland	Forestland	Grassland	Water	Built-Up Land	Unused Land
Cropland	22,209	0	3	52	223	1
Forestland	4	315,677	32	76	101	3
Grassland	88	28	1,231,264	1827	349	97
Water	1	49	59	126,681	24	718
Built-up land	5	0	11	92	1612	29
Unused land	25	7	140	3581	242	812,841

From 2010 to 2020, the areas of cropland, forestland, grassland, and unused land on the QTP decreased by 156 km^2, 132 km^2, 2144 km^2, and 3147 km^2, respectively, while the areas of water and built-up land increased by 4777 km^2 and 802 km^2, respectively, in Table 6. In 2020, the areas of different land use types on QTP were grassland, unused land, forestland, water, cropland, and built-up land in descending order. In 2020, built-up land accounted for less than 0.1% of the total area, but compared with that in 2010, the built-up land area had increased by nearly 46%, indicating that human activities on the QTP were getting stronger. These likely led to an increase in ecological risk on the QTP.

Table 6. Area and proportion of each land use type.

Land Use Type	2010		2020		2030 Natural Development Scenario		2030 Ecological Conservation Scenario	
	Area /km^2	Proportion /%	Area/km^2	Proportion/%	Area /km^2	Proportion/%	Area /km^2	Proportion /%
Cropland	22,488	0.89	22,332	0.89	22,180	0.88	22,172	0.88
Forestland	315,893	12.54	315,761	12.54	315,631	12.53	315,761	12.54
Grassland	1,233,653	48.99	1,231,509	48.91	1,229,376	48.82	1,231,669	48.91
Water	127,532	5.06	132,309	5.25	134,724	5.35	136,000	5.40
Built-up land	1749	0.07	2551	0.10	3288	0.13	2570	0.10
Unused land	816,836	32.44	813,689	32.31	812,952	32.28	809,979	32.17

The trends in land use change for the future natural development scenario and the ecological conservation scenario differ from one another. In the natural development scenario, the land use change trend for 2020 to 2030 is nearly the same as that for 2010 to 2020. The areas of cropland, forestland, grassland, and unused land decrease, while the area of other land increases. In the ecological conservation scenario, the areas of grassland, water, and built-up land gradually increase, while the area of forestland does not change. Cropland and unused land decrease. This indicates that, in the ecological conservation scenario, forestland and grassland, as the main ecological land, are effectively protected. Compared with the natural development scenario, the areas of forestland and grassland increase by 130 km^2 and 2293 km^2, respectively, and the area of built-up land decreases by 718 km^2.

3.2. Landscape Ecological Risk Spatiotemporal Change

Land use type and its change affected landscape ecological risk in the QTP. The natural break point method was adopted to divide the landscape ecological risk value of the QTP into five levels: lower ecological risk ($ERI \leq 0.014$), low ecological risk ($0.014 < ERI \leq 0.024$), medium ecological risk ($0.024 < ERI \leq 0.031$), high ecological risk ($0.031 < ERI \leq 0.038$), and higher ecological risk ($0.038 < ERI$).

The higher ecological risk areas of the QTP were mainly distributed in its northern part and that the land use type was mainly unused land in Figure 5. Lower, low, and medium ecological risk areas were mainly distributed in the southern part of the QTP, and the land use types were mainly forestland and grassland. High risk areas were mainly distributed in higher risk areas.

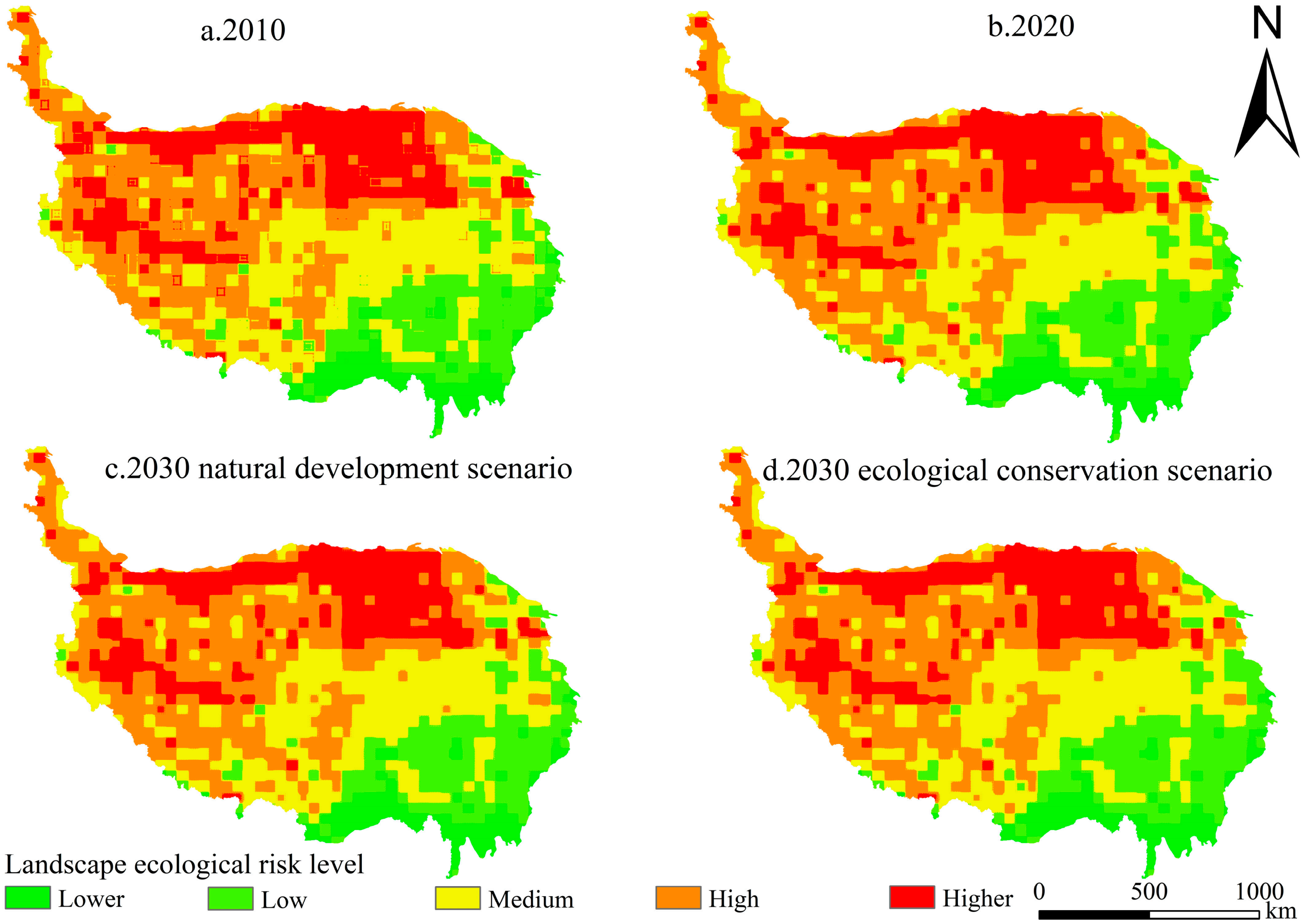

Figure 5. Spatial pattern of each landscape ecological risk level from 2010 to 2030.

From 2010 to 2020, the areas of low, medium, and high ecological risk on the QTP had an increasing trend, increasing by 505 km^2, 12,358 km^2, and 9270 km^2, respectively; while the areas of lower and higher risk had a decreasing trend, decreasing by 4043 km^2 and 18,089 km^2, respectively, in Table 7. This indicated that the overall ecological risk of the QTP increased during from 2010 to 2020, but the ecological risk in some higher-risk areas was alleviated. In 2020, the landscape ecological risks on the QTP were mainly medium, high, and higher ecological risks, accounting for 27.85%, 32.57%, and 19.02% of the total area, respectively; 14.37% of the low-risk area and 6.19% of the lower risk area. In the simulation results for 2030 under the two scenarios, the landscape ecological risk area of the QTP at all levels is still dominated by the area proportion of medium, high, and higher ecological risk area. The area proportion of low ecological risk area, and the area proportion of lower ecological risk area is the smallest. Under the natural development scenario, the five types of ecological risk area account for 27.78%, 32.51%, 19.15%, 14.40%, and 6.15%, respectively, while under the ecological conservation scenario, the five types of ecological risk area account for 27.53%, 32.77%, 18.89%, 14.50%, and 6.31%, respectively.

Table 7. The area and proportion of each landscape ecological risk level.

Risk Level	2010		2020		2030 Natural Development Scenario		2030 Ecological Conservation Scenario	
	Area /km^2	Proportion /%	Area/km^2	Proportion/%	Area /km^2	Proportion/%	Area /km^2	Proportion /%
Lower	159,902	6.35	155,859	6.19	155,010	6.15	159,054	6.31
Low	361,547	14.35	362,052	14.37	362,831	14.40	365,315	14.50
Medium	689,052	27.36	701,410	27.85	699,742	27.78	693,409	27.53
High	811,201	32.21	820,471	32.57	818,901	32.51	825,302	32.77
Higher	497,090	19.74	479,001	19.02	482,309	19.15	475,712	18.89

Compared with the natural development scenario, under the ecological conservation scenario, the areas of lower and low ecological risk areas increase by 4044 km^2 and 2484 km^2, respectively, and the areas of medium and higher ecological risk areas decrease by 6333 km^2 and 6597 km^2 in 2030, respectively. Therefore, the implementation of ecological conservation does indeed reduce the ecological risk of the QTP.

4. Discussion

4.1. Land Use Simulation and Its Results

Regarding the selection of driving factors for land use simulation, different from Zhou et al. [55], this study not only selected some conventional factors, but also innovatively added the driving factor of frozen soil to participate in the calculation of the model according to the actual situation of the QTP. The reason for this was that there is a large amount of frozen soil distribution on the QTP. Existing studies show that the degradation of frozen soil increases the active layer, which increases soil water infiltration, reduces surface soil water, and leads to vegetation degradation, thus causing a change in land use type [56,57].

According to the simulation results, in both the ecological conservation scenario and the natural development scenario, in 2030, the area of cropland will decrease and the area of water will increase, which is consistent with the research results of Zhou et al. [55]. The decrease in cropland area is due to the implementation of ecological fallowing policies [58], while the increase in water area is due to the melting of glaciers and frozen soil on the QTP. This melting is caused by global warming, increasing surface runoff, and water from lakes and rivers [59]. The differences between this study and that of Zhou et al. are as follows: The Kappa coefficient of this study is higher than that of Zhou et al. Moreover, this study showed the future land use pattern for each land use type, while the study of Zhou et al. did not.

4.2. Landscape Ecological Risk Results

Overall, the results of our study were highly consistent with the results of Wang et al. [60] and Wang et al. [61] regarding the current landscape ecological risk of the QTP; however, differences existed between our study and these two studies with respect to the western QTP. Our landscape ecological risk of the western QTP is higher than that of the two studies because of our higher vulnerability value for grassland. Grassland is an important part of the QTP ecosystem, and grassland degradation has become a major threat to the QTP's ecological security [62]. Therefore, this study assigns a higher vulnerability value to grassland.

4.3. Policy Implications

In the context of policy formation, we propose that in the high landscape ecological risk areas of the northwestern QTP human activities, especially overgrazing, should be strictly controlled; nature reserves and national parks should be established to reduce the landscape ecological risk. Moreover, protecting frozen soil, in the construction of infrastructure and in mining, should be a priority.

4.4. Advantages, Limitations and Future Work

Landscape ecological risk assessment of the QTP in this study combined geographical processes and ecological processes. Using this combination and a PLUS model effectively revealed the past, present, and future ecological risk changes of the QTP. The potential application of the research results lies in the construction of ecological reserves.

Of course, our study had some limitations. The QTP is a large region and has a complex internal ecosystem, which is composed of a number of physical geographical areas with their own characteristics. However, the results obtained in this study are a whole result, and the landscape ecological risk of each physical geographical area has not been evaluated. Therefore, in the future, the landscape ecological risk analysis of the QTP will be comprehensively analyzed by combining the different natural and social-economic factors of each physical geographical area.

5. Conclusions

In this study, the PLUS model and landscape ecological risk index were used to analyze the past, present, and future land use patterns and landscape-ecological risk changes on the QTP. The results are as follows:

1. Under the natural development scenario, the land use pattern and change trend of the QTP during 2020–2030 were basically the same as that during 2010–2020. The area of cropland, forestland, grassland, and unused land was gradually smaller, while the area of other land use types was constantly increasing. The areas of forest land did not change, the area of cropland and unused land decreased, and the area of forestland and grassland increased by 130 km^2 and 2293 km^2, respectively, compared with the natural scenario.
2. Under the natural development scenario, the overall ecological risk for the QTP increased from 2010 to 2030.This indicates that the proportion of low ecological risk area decreased, while the proportions of medium and high ecological risk area increased. In the ecological conservation scenario, compared with the natural development scenario, the area of lower, low, and high ecological risk increased by 4044 km^2, 2484 km^2, and 6401 km^2 respectively, while the area of medium and high ecological risk decreased by 6333 km^2 and 6597 km^2 respectively.

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