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RESEARCH ARTICLE

Scenario-based ecological security patterns to indicate landscape sustainability: a case study on the Qinghai-Tibet Plateau

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Abstract
Context When setting the goal of landscape sustainability in landscape management, a key theoretical question should be which landscape patterns are more sustainable, whereas there were few studies that further compared optimization scenarios.
Objectives This article sought to identify the future scenario of landscape services and the most sustainable landscape in the Qinghai-Tibet Plateau.
Methods This study adopts the parameter of ecological security pattern (ESP) combining with landscape connectivity and landscape service as indicators to assess the sustainability of landscape patterns in 2010, 2020 and 2030 with different land use scenarios in Representative Concentration Pathways.
Results The results showed that (1) the area with high quality of the three landscape services was mainly concentrated in the southeast of the Qinghai-Tibet Plateau, where a large area of forest was distributed, and the low quality area was located in the northwest, which was bare land in 2010; (2) the landscape services showed a declining trend under the RCP 2.6 and RCP 4.5 scenarios from 2020 to 2030, whereas the values remained stable under the RCP 6.0 and RCP 8.5 scenarios; and (3) there were 9 ecological sources and 16–17 corridors within the ESP scenarios with quantitative parameters to indicate the landscape sustainability of the scenarios.
Conclusions The approach of this study showed the possibility of using ESP scenarios to quantitatively indicate the sustainability of landscape patterns and provide guidance for future landscape management.

Keywords Landscape services · Ecological security pattern · Scenario analysis · Landscape sustainability · Qinghai-Tibet Plateau

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Introduction

Landscape sustainability is regarded as the comprehensive ability of the specific landscape to have long-term and stable provision of landscape services and maintain and improve human well-being in the region (Turner et al. 2013; Wu 2013). The many recent environmental problems (i.e., soil erosion, vegetation destruction, biodiversity decline, etc.) have led to ecological degradation and weakened ecosystem stability at the landscape scale (Lei et al. 2016). Sustainable landscape patterns can strengthen the landscape to adapt to environmental changes (Potschin and Haines-Young 2013; Wu and Wu 2013). For example, a sustainable landscape pattern conforms to the spatial organization of geographical elements by regulating the spatial allocation of the landscape (Fan et al. 2019). To solve ecological problems from the landscape perspective, integrating indicators and methodologies to evaluate sustainable landscape patterns is required under the ultimate goal of achieving landscape sustainability (Bettencourt and Kaur 2011; Huang et al. 2019).

Ecological security patterns (ESPs) have been applied as an effective approach that identifies the necessary steps to protect regional security (Peng et al. 2018; Zhao et al. 2019b). The ESPs are defined as the vital and simplified landscape patterns that indicate important patches, locations, and spatial connections and are used with the objective of optimizing the landscape structure and process (Yu 1996). Constructing ESPs is a specific practical method for adjusting the spatial structure of landscape, which has the potential to improve the positive ecological processes through connectivity (Su et al. 2016; Zhang et al. 2015) to enhance the maximization of landscape services and achieve sustainable landscape patterns. The "source-corridor" framework is widely used to construct regional ESPs (Li et al. 2019; Wang and Pan 2019), which could meet the requirements of landscape sustainable development (Potschin and Haines-Young 2013). For instance, ecological sources are landscape patches that prove the essential and stable patterns of ecological resources in landscape sustainability; ecological corridors are narrow regions connecting ecological sources that effectively enhance the ecological connectivity of landscapes to improve the landscape's resistance and stability.

The ESPs have the potential to be treated as potential quantifiable tools to instruct landscape sustainability efforts and have the advantage of integrating landscape patterns and landscape services. Specifically, the source corridors in ESPs can be interpreted as the quantification parameter of the classic indicators in the "source-corridor" framework. Compared with the traditional landscape metrics that reflect landscape pattern conditions (Hou et al. 2020), ESPs can more comprehensively reflect landscape connectivity and services after ecological restoration and reconstruction (Peng et al. 2019). Therefore, the parameters of ESPs could be regarded as the evaluation indicators of sustainable landscape characteristics, especially at large landscape scales.

However, the application of constructing ESPs doesn't seem perfect. For example, the structure of simulated landscape patterns would encounter some obstructions, including geological conditions, climate and economic cost (Zhang et al. 2016). Moreover, ESPs often fail to reflect the long-term sustainability of landscapes, as the construction of ESPs is usually based on the current situation of research time (Peng et al. 2019). The built ESPs often cannot represent the continuing change of external factors on landscape for only depending on the specific time of research (Fraedrich et al. 2016). In addition, the landscape changes can be severely affected by climate change (Hao et al. 2017a; Zhao et al. 2019a), and may lead to an unsustainable landscape (Djalante 2019). Therefore, it is necessary to predict the landscape patterns under different future climate scenarios (Liu et al. 2019; Kim et al. 2013). If the landscape patterns under future climate scenarios can be combined with ESPs, this will become an important tool for assessing and managing landscape sustainability at the long-term scale.

To cope with the potential landscape pattern changes and sustain the regional landscape sustainability in the future, we introduced ESP scenario analysis based on the "source-corridor" framework, circuit theory, and the change of landscape services. The landscape system in Qinghai-Tibet Plateau is vulnerable (Liu et al. 2018), and the landscape pattern changes in this vulnerable region have aroused several research attentions (Li et al. 2015; Qian et al. 2017; Chen and Shi 2018). According to the often-used landscape pattern indices cannot represent landscape sustainability, it is essential for integrated understanding the multiple attributes of landscape sustainability, such as typical landscape services, landscape connection, and the future landscape scenarios in Qinghai-Tibet Plateau. Therefore, we used the scenarios of ESPs to analyze two main questions in this article: (1)

What is the future scenario of landscape services in the Qinghai-Tibet Plateau? (2) Which ESP scenario is more sustainable in the future landscape of the Qinghai-Tibet Plateau?

Study area and data

Study area

The Qinghai-Tibet Plateau (26°00′–39°47′N, 73°19′–104°47′E) is located on the first step of China and southwest China. Because the Qinghai-Tibet Plateau is the highest altitude plateau in the world, it is called the "Roof of the World". Its territory is approximately 2.5 million km^2. This region has a special plateau mountain climate due to the altitude and terrain. The Qinghai-Tibet Plateau can be geographically consisted of ten natural zones (Zheng 2008), and this study combined them into nine zones through mingle these natural zones according to two zones situated the same mountain chain of Kunlun with desert condition: East Sichuan-Tibet deep valley coniferous forest zone, Kunlun Mountain desert zone, Guolu Naqu mountainous alpine shrub meadow zone, Qaidam Basin desert zone, Qiangtang Plateau lake basin the cold and steppe zone, Southern Tibet the high valley shrubland zone, Ali Mountain desert zone, Qilian Qingdong Mountain basin coniferous forest and grassland zone, and Qingnan Plateau wide valley alpine meadow grassland zone (Fig. 1).

Data sources

This study contains several datasets as follows. (1) Land use data and simulated land use data (RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5) were obtained from the Department of Earth System Science of Tsinghua University (https://data.ess.tsinghua.edu.cn/) for 2010, 2020 and 2030, which had a 1 km resolution with eight classification types: cropland, forest, grassland, shrubland, water, urban, snow, and bare land (Li et al. 2016). (2) Net primary production (NPP) data with a resolution of 500 m were obtained from the United States Geological Survey (USGS) website (https://www.usgs.gov/) via the MOD17A3H product. (3) A digital elevation model (DEM) of GDEMV2 with a 30 m resolution were downloaded from the Geospatial Data Cloud (https://www.gscloud.cn/). (4) Soil attribution data with a resolution of 30 s were acquired from the Harmonized World Soil Database (https://www.fao.org/). (5) The precipitation data with 0.1° resolution were derived from the multi-source weighted-ensemble precipitation (MSWEP) data (https://gloh2o.org/). (6) The watershed data were downloaded from HydroSHEDS (https://hydrosheds.org/). To show the responses of the landscape services to landscape change under different climate scenarios, we unified the times of the evaluation parameters in 2010, except for land use data. All data resolutions were resampled to 1 km through cubic convolution interpolation.

Methods

Landscape services are the benefits for humans from ecosystem services at the landscape scale (Bastian et al. 2014; Nowak and Grunewald 2018Charles et al. 2020;). Based on "source-corridor" framework, landscape services could be used to identify ecological sources. Ecological resistance, which is the essential factor for constructing ecological corridors, is evaluated by land use types and elevation. Additionally, we constructed the ESPs based on circuit theory under different landscape patterns scenarios. With four kinds of RCPs in both 2020 and 2030, there were eight kinds of ESP scenarios in this study (Fig. 2).

Landscape service evaluation

The carbon sequestration, soil conservation, water retention and habitat quality are typical ecosystem services at landscape scale and often mapped in ESPs studies (Li et al. 2020; Peng et al. 2018). However, water retention is hard to be precisely mapped in Qinghai-Tibet Plateau because of the uncertainty in glaciers melting as well as the variations of frozen soil. Therefore, we only adopt the three commonly used ecosystem service maps to represent landscape services.

Carbon sequestration

Carbon sequestration refers to when an organism transforms carbon dioxide into organic carbon through photosynthesis (Jiang et al. 2016). The NPP could reflect the ability of organisms to fix carbon dioxide

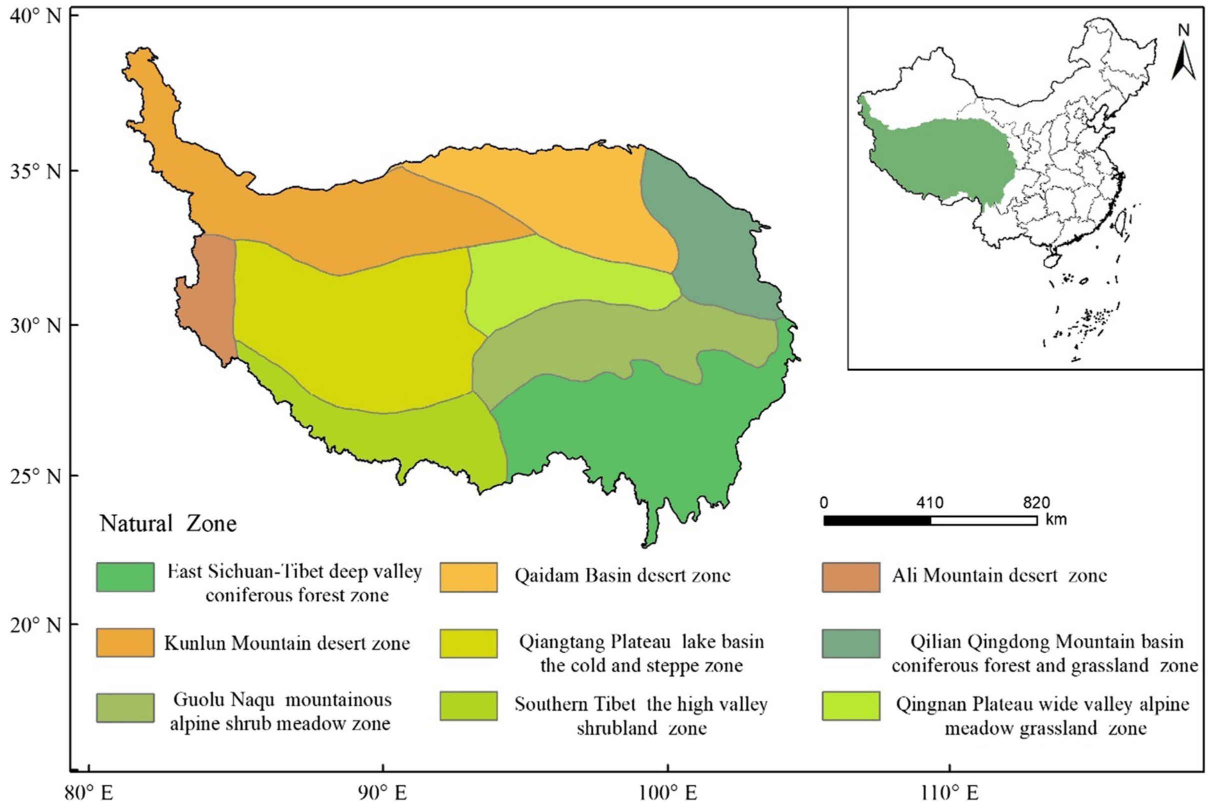

Fig. 1 The locations of the natural zones on the Qinghai-Tibet Plateau

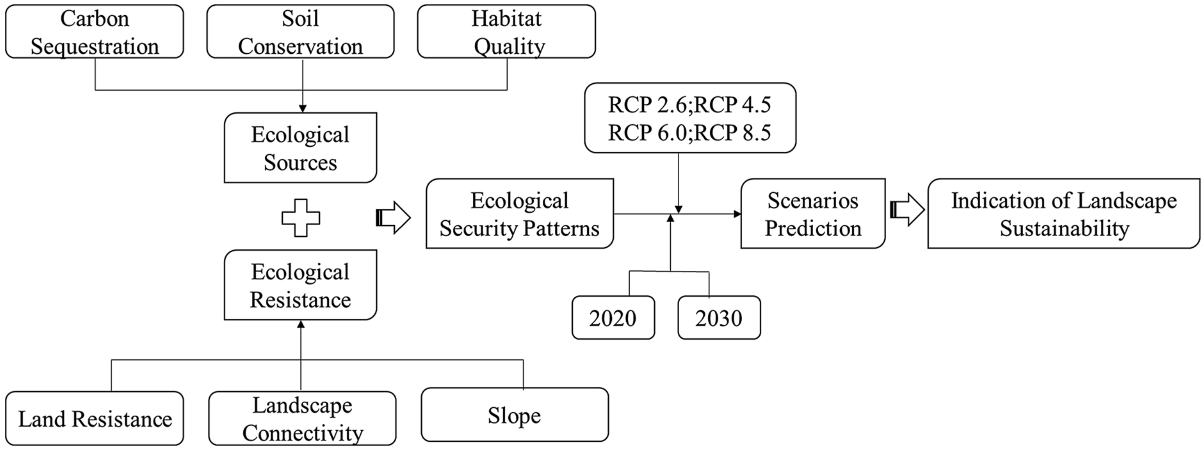

Fig. 2 The framework of the methodology

(Hao et al. 2017b). Therefore, carbon sequestration was replaced by NPP in this study. Based on the selected control variables in different landscape scenarios, this study extracted the average NPP from the 12th level watersheds (level defined in HydroSHEDS) of forest, grassland, shrubland and cropland areas from 2010 and assigned the mean value of each land use type to each watershed in different scenarios. The specific calculation process is as follows:

$$CS = NPP_f + NPP_p + NPP_s + NPP_c$$

$$NPP_t = \sum_{i=1}^{n} (NPP_{ti2010} \times A_{ti})$$

whereCS is the carbon sequestration, NPP_f, NPP_p, NPP_s and NPP_c are the total NPP of the forest, grassland, shrubland and cropland, respectively; NPP_t is the total *NPP* for land use type *t* in different scenarios; *i* from 1 to n represents every basin of the 12 basin levels; NPP_{ti2010} is the average *NPP* in basin *i* for land use type *t* in 2010; and A_{ti} is the area of the land use type in basin *i* in the different scenarios.

Soil conservation

Soil conservation refers to the difference between the potential soil erosion and the actual soil erosion (Qiao et al. 2019). The InVEST model, which considers the factors of soil erosion, slope, vegetation coverage and management measures, was applied to assess the soil conservation. The calculation equation is as follows (Li et al. 2018):

$$A_r = A_p - A_a$$

$$A_p = R \times K \times LS$$

$$A_p = R \times K \times LS \times C \times P$$

where A_r is the soil conservation (t); A_p and A_a are the amount of potential soil erosion and actual soil erosion (t), respectively; R is the rainfall erosion factor; K is the soil erodibility factor; LS represents the slope length and gradient factor; C is vegetable coverage and management factor; and P is measure of soil conservation.

Habitat quality

Habitat quality refers to the ability of an ecosystem to provide a suitable environment for organisms (Terrado et al. 2015). High habitat quality has the potential to host abundant biodiversity. The InVEST model is often used to assess habitat quality (Sallustio et al. 2017; Sun et al. 2019). The calculation processes are as follows:

$$Q_{xj} = H_j\left(1 - \left(\frac{D_{xj}^z}{D_{xj}^z + K^z}\right)\right)$$

$$D_{xj} = \sum_{r=1}^{R}\sum_{y=1}^{Y_r}\left(\frac{W_r}{\sum_{r=1}^{R} W_r}\right) r_y i_{rxy} \beta_x S_{jr}$$

where Q_{xj} is the habitat quality of raster x in land use type j; H_j is the habitat suitability of land use type j; D_{xj} is the total threat level of grid x in land use type j; R is the number of threat sources; Y_r is the set of grid cells on r raster map with threat sources; W_r is the threat source weights; r_y is the stress value of raster *r*; i_{rxy} is the stress level of r_y to raster x; β_x is the accessibility of the threat sources to raster x; S_{jr} is the sensitivity for threat sources of land use type *j*; and *K* and *Z* are scale factors.

Ecological security pattern construction

Ecological source identification

Ecological sources are essential ecological patches for the continual provision of ecosystem services (Peng et al. 2019). This study adopted three landscape services (carbon sequestration, soil conservation, habitat quality) to identify the ecological sources and normalization of three landscape services and then summed the standardized value of these results. In addition, considering the differences in the environmental characteristics of nine natural zones in the Qinghai-Tibet Plateau (Zhang et al. 2010), this study set up different thresholds to select ecological sources in nine natural zones based on the landscape services. Specifically, first, we added up the sum of the landscape services in every natural zone; then, we used natural breaks to divide all landscape services into 5 levels and extracted the highest level as the alternative region of the sources (Table 1); Finally, to ensure the stability of the landscape service supply for the sources, we set the minimum source area to 2000 km^2 to limit the patch numbers with high landscape services in every natural zone.

Ecological resistance setting

Ecological resistance refers to the number of obstacles for species in ecological processes and represents the connectivity of a heterogenous landscape heterogeneity for species migration (Beier et al. 2008). The comprehensive factors of land use types, landscape connectivity and slope were used to construct the

Table 1 The threshold of the landscape services in every natural zone

Natural zones	Landscape service threshold	Natural zones	Landscape service threshold
Qiangtang Plateau lake basin the cold and steppe zone	0.91	Guolu Naqu mountainous alpine shrub meadow zone	1.40
Ali Mountain desert zone	0.87	East Sichuan-Tibet deep valley coniferous forest zone	1.82
Southern Tibet the high valley shrubland zone	1.06	Qilian Qingdong Mountain basin coniferous forest and grassland zone	1.37
Kunlun Mountain desert zone	0.81	Qaidam Basin desert zone	0.88
Qingnan Plateau wide valley alpine meadow grassland zone	0.88		

ecological resistance of the Qinghai-Tibet Plateau. *Fragstats 4.2* software (McGarigal and Marks 1995) was applied to identify the landscape connections with forest, grassland, shrubland and water. The calculation formulas are as follows:

$$R = R_{land} \times (1 - R_{connect}) \times R_{slope}$$

$$X = \frac{x - x_{min}}{x_{max} - x_{min}}$$

$$C = \left[\frac{\sum_{i=1}^{m} \sum_{j=k}^{n} c_{ijk}}{\sum_{i=1}^{m} \left(\frac{n_i(n_i - 1)}{2} \right)} \right] (100)$$

$$S = \frac{h}{l}$$

where R is the ecological resistance; R_{land} is the resistance value of the land use type (Table 2) (Gurrutxaga et al. 2011; Zhang et al. 2016); $R_{connect}$ and R_{slope} are the normalization values for the landscape connection and slope, respectively; X is a standardized value; and x_{min} and x_{max} are the minimum and maximum values of x, respectively, and x belongs to X and standardizes both R_{land} and R_{slope}; C is the landscape connectivity; c_{ijk} is the connection between patch j and k (0 = unjoined, 1 = joined) of the same patch type i; n_i is the number of patches in the landscape of each patch type i; S represents the slope; and h and l are the altitude and the horizontal distance, respectively.

Ecological corridor identification

Ecological corridors are the conduits of the flow of materials and energy among different ecological sources in the region (Zhang et al. 2016). Circuit theory was used to identify the ecological corridors and pinch points through the *Linkage Mapper Toolkit* within *ArcGIS 10.5*, which was derived from *Circuitscape 4.0.5* (McRae et al. 2016). Circuit theory models the movement of species or energy in landscapes based on the characteristics of the random walks of electrons in circuits (Dickson et al. 2019) and regard the landscape as the conductive surface and the species or energy as the electrons. Circuit theory combines graph theory and Ohm's law, and the formula is as follows:

$$I = \frac{U}{R}$$

Table 2 The ecological resistance of the different land use types

Land use types	Forest	Shrubland	Grassland	Cropland	Water	Bare land	Snow	Urban
Resistance value	1	5	10	30	50	300	400	500

where I represent the current, U is the voltage, and R is the electrical resistance.

Moreover, the ecological importance of the parameters is as follows (Table 3) (Doyle 1984):

In addition, the pinch points refer to the regions that are essential for species migration or energy flow in the corridors, which play an important role in landscape connectivity (McRae et al. 2008). If the landscape is insecure in the pinch point regions, the impact will be far greater than in the other areas.

Results

The landscape services scenarios

As shown in Fig. 3, the high quality areas of the three landscape services were mainly concentrated in the East Sichuan-Tibet deep valley coniferous forest zone and Guolu Naqu mountainous alpine shrub meadow zone of Qinghai-Tibet Plateau, and the low quality areas of the three landscape services were located in the Kunlun Mountain desert zone and Qaidam Basin desert zone in 2010. The average value of soil conservation was 3037 t, and the values were below average in many areas, especially in the Qaidam Basin desert zone, with an average of 277 t; Qingnan Plateau wide valley alpine meadow grassland zone, with an average of 377 t; and Kunlun Mountain desert zone, with an average of 512 t. The minimum value was below 10 t, whereas the maximum value was above 2000 t. For carbon sequestration, the value ranged between 0 t/hm^2 and 1.77 t/hm^2, and the average value was 0.12 t/hm^2, and the values were above the average in many zones, except the Kunlun Mountain desert zone, which had a minimum value of 0.01 t/hm^2. The decrease from east to west and the low value can be attributed to the low vegetation coverage at high altitudes. The habitat quality value ranged from 0 to 1, and the average value was 0.54. The high value areas for habitat quality was located in the Guolu Naqu mountainous alpine shrub meadow zone, which had an average value of 0.77, and the Qilian Qingdong Mountain basin coniferous forest and grassland zone, which had an average value of 0.73 that was concentrated in the water and forest areas. The low values were located in the Kunlun Mountain desert zone, with an average of 0.19, and the Qaidam Basin desert zone, with an average of 0.23.

As shown in Fig. 4, considering the land use types in different climate scenarios in the future, the total value of the three landscape services represented obvious changes. From 2020 to 2030, the three landscape services under the RCP 6.0 and RCP 8.5 scenarios varied little comparing with 2010. Specifically, the total value of soil conservation showed a decreasing trend under the RCP 2.6 scenario, from 11.592×10^9 t in 2010 to 11.586×10^9 t in 2020 to 11.568×10^9 t in 2030. Under RCP 4.5 scenario, the soil conservation increased in 2020 by 11.598×10^9 t and then decreased in 2030 by 11.573×10^9 t compared with the soil conservation in 2010. However, under the other two scenarios in RCP 6.0 and RCP 8.5, the total value of soil conservation remained stable, with a value of approximately 11.592×10^9 t.

For carbon sequestration, the total value of the carbon sequestration services tended to decline from 2010 to 2030 under every scenario. Among these declines, the largest was in scenario RCP 4.5, which showed a decrease from 29.549×10^4 t/hm^2 in 2010 to 29.538×10^4 t/hm^2 in 2020 to 29.506×10^4 t/hm^2 in 2030. The smallest declines occurred in scenarios RCP 6.0 and RCP 8.5, which fluctuated at 29.540×10^4 t/hm^2, and its fluctuation range did not

Table 3 The ecological parameters in circuit theory

The parameters	Ecological importance
Current (I)	This metric reflects the net amount of time for species or energy to reach the target habitat through the corresponding corridors in the ecological process. The higher the current value is, the higher the net migration probability
Voltage (U)	This variable presents the probability of leaving a source to a given target source in an ecological process
Electric resistance (R)	This metric reflects the degree of impediment for species or energy flow in an ecological process

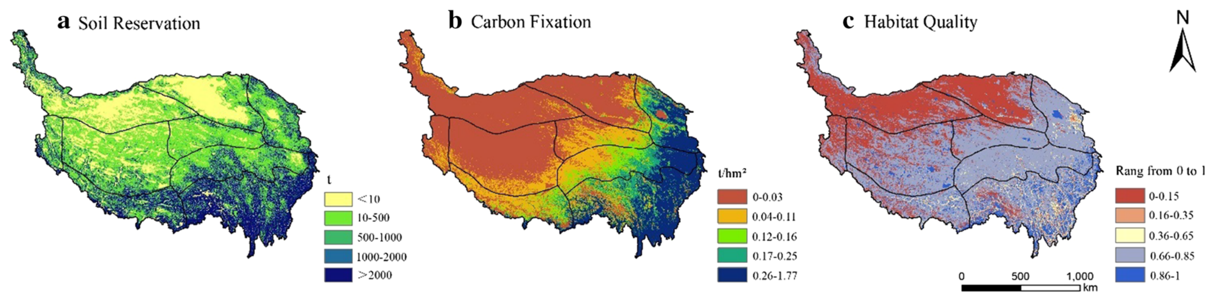

Fig. 3 Spatial distribution of landscape services on the Qinghai-Tibet Plateau in 2010

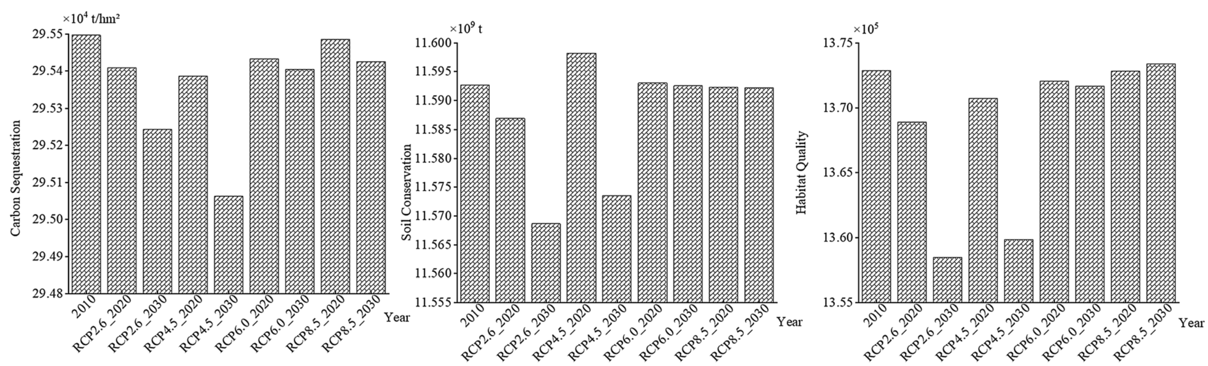

Fig. 4 The total value of landscape services under the different scenarios

exceed 100 t/hm^2. The habitat quality exhibited different change trends. The most obvious decline was that in the RCP 2.6 scenario from 13.728 $\times$ 10^5 in 2010 to 13.689 $\times$ 10^5 in 2020 and to 13.584 $\times$ 10^5 in 2030. The total value of habitat quality declined from 13.728 $\times$ 10^5 in 2010 to 13.707 $\times$ 10^5 in 2020 and to 13.598 $\times$ 10^5 in 2030 in the RCP 4.5 scenario. In addition, there was little change under RCP 6.0 scenario, during which the value remained in the range of 13.700 $\times$ 10^5. Under RCP 8.5, the total value of habitat quality even exhibited a small increase, from 13.728 $\times$ 10^5 in 2010 to 13.734 $\times$ 10^5 in 2030.

The scenarios of ecological sources and corridors

According to the threshold (Table 1), this study selected nine ecological sources under different scenarios in ESPs (Fig. 5). The ecological sources mainly consisted of grasslands and forests, which were mainly distributed at the junction of the natural zones. This phenomenon had the advantage of strengthening the ecological connection between the different natural zones. The ecological sources only occupied a small area in the entire region, accounting for between only 3.7% and 3.8% of the area among the scenarios. The area of the ecological sources decreased from 2020 to 2030 under the RCP 2.6 and RCP 4.5 scenarios from 96,853 km^2 in 2020 to 95,919 km^2 and from 97,187 km^2 to 94,698 km^2, respectively. Under the RCP 6.0 and RCP 8.5 scenarios, the area of the ecological sources was greater than 97,000 km^2, and especially under the RCP 8.5 scenario, the area of the ecological sources obviously increased from 97,216 km^2 in 2020 to 98,026 km^2 in 2030 (Table 4). In general, compared with the different scenarios, the RCP 2.6 and RCP 4.5 scenarios had lower ecological source areas that indicated lower protection costs, especially the RCP 2.6 scenario.

The ecological sources that provided the landscape services were diverse (Table 5). The area of the ecological sources that had obvious changes led to a change in soil conservation but had little effect on the other two landscape services. In the RCP 2.6 scenario, the area of the ecological source area is reduced, and carbon sequestration services are not reduced. The habitat quality was only reduced by 0.007 km^2, whereas the soil conservation apparently increased from 6017.797 t/km^2 in 2020 to 6138.299 t/km^2 in

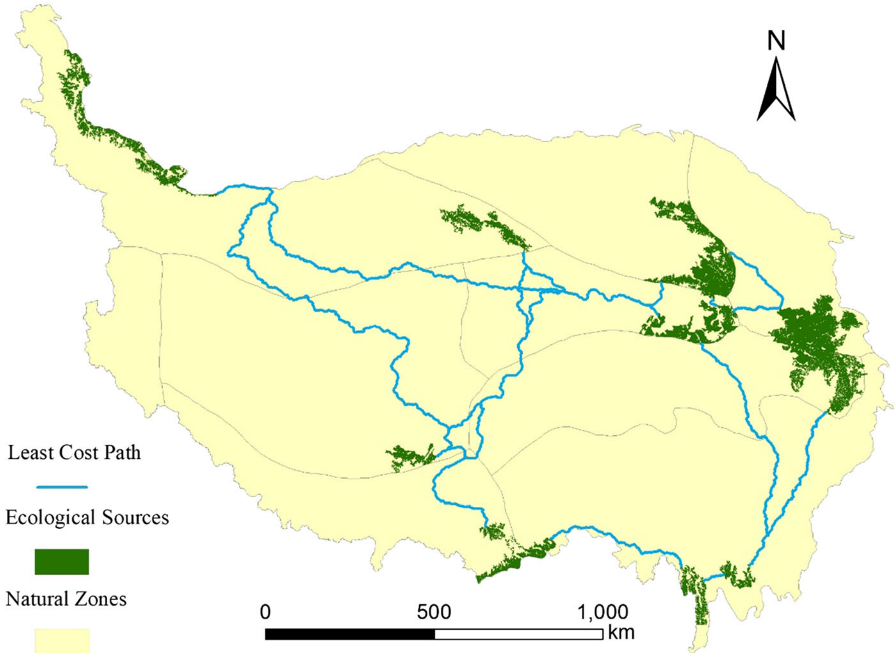

Fig. 5 The locations of the ecological sources and corridors in the ESPs under RCP 2.6 in 2020

Table 4 Information on the ecological sources and corridors in ESPs under different scenarios

Ecological indicators	RCP 2.6 (2020)	RCP 2.6 (2030)	RCP 4.5 (2020)	RCP 4.5 (2030)	RCP 6.0 (2020)	RCP 6.0 (2030)	RCP 8.5 (2020)	RCP 8.5 (2030)
The area of ecological sources (km^2) (the percentage of regional area %)	96,853 (3.81)	95,919 (3.77)	97,187 (3.82)	94,698 (3.72)	97,150 (3.82)	97,092 (3.81)	97,216 (3.82)	98,026 (3.85)
Ecological sources average soil conservation (t/km^2)	6017.797	6138.299	6461.094	5634.447	6464.391	6463.948	6452.312	6429.706
Ecological sources average carbon sequestration ($t/hm^2/km^2$)	0.228	0.227	0.23	0.223	0.23	0.23	0.229	0.231
Ecological sources average habitat quality (km^2)	0.816	0.809	0.811	0.804	0.812	0.811	0.811	0.812
The number of corridors	16	16	16	17	16	16	16	16
The average length of corridors (km)	13,489.641	13,600.612	13,503.497	14,554.395	13,495.055	13,528.669	13,515.196	13,511.096

2030. Under the RCP 4.5 scenario, as the ecological sources decreased from 97,187 km^2 in 2020 to 94,698 km^2 in 2030, the average soil conservation in ecological sources were reduced from 6461.094 t in 2020 to 5634.447 t in 2030, while the carbon sequestration and habitat quality showed little change.

Table 5 Information on ESPs with circuit theory under different scenarios

Ecological indicators	RCP 2.6 (2020)	RCP 2.6 (2030)	RCP 4.5 (2020)	RCP 4.5 (2030)	RCP 6.0 (2020)	RCP 6.0 (2030)	RCP 8.5 (2020)	RCP 8.5 (2030)
The average resistance in the corridors (Ω/km^2)	0.876	0.869	0.871	0.859	0.877	0.891	0.875	0.885
The total current in the corridors (A)	56,934	56,991	57,058	57,173	57,066	57,029	57,024	57,048
The average current in the corridors (A/km^2)	0.369	0.367	0.365	0.352	0.37	0.369	0.368	0.374

Under the RCP 6.0 and RCP 8.5 scenarios, the three landscape services did not change owing to the small change in the area of the ecological sources.

There were 16 or 17 ecological corridors in the ESPs under the 8 scenarios, which connected the 9 ecological sources from the natural zones. The ecological corridors showed that the middle part of the study area was more complicated than the other parts, and the curvature of the corridors was predicted to be different under the eight scenarios. Under the RCP 2.6 scenario, although the area of the ecological sources decreased and the number of corridors did not change, the average length of the corridors increased from 13,489.641 km in 2020 to 13,600.612 km in 2030. under the RCP 4.5 scenario, an ecological corridor was added in the southeast of the study area, which significantly lengthened the average length of the corridors from 13,503.497 km in 2020 to 14,554.395 km in 2030. This phenomenon could increase the possibility of species migration or energy flow. Under the RCP 6.0 and RCP 8.5 scenarios, there were almost no changes in the numbers of corridors and the average lengths of the corridors, which indicated more stable ecological security patterns (Table 4).

Therefore, based on the ecological sources and corridors and the landscape services provided by ecological sources, the ESP scenario under RCP 8.5 was assessed to be the most sustainable landscape pattern from 2020 to 2030.

The circuit theory scenarios

In general, the magnitude of species migration or energy flow mainly concentrates on the central Qinghai-Tibet Plateau in all scenarios, which according to these regions have large currents and the large corridor widths in the ESPs. In the northwest of the study area, due to its high altitude, low vegetation coverage and high ecological resistance, the corridor widths were narrow, and there was only one path. The locations of the pinch points that presented the high current regions were basically unchanged and were mainly located in two zones: the Kunlun Mountain desert zone and the Qingnan Plateau wide valley alpine meadow grassland zone (Fig. 6). Comparing the different scenarios, the ecological resistance in the corridors decreased from 2020 to 2030 under the RCP 2.6 and RCP 4.5 scenarios, whereas the value increased under RCP 6.0 and RCP 8.5 scenarios. Specifically, in the RCP 2.6 scenario, the ecological resistance in the corridors decreased from 0.876 Ω/km^2 in 2010 to 0.869 Ω/km^2 in 2030. Under scenario 4.5, the ecological resistance in corridors decreased from 0.871 Ω/km^2 in 2010 to 0.859 Ω/km^2 in 2030. Under the scenarios of RCP 6.0 and RCP 8.5, the range of the increase in ecological resistance in the corridors was greater than that of the decrease, which increased by 0.014 Ω/km^2 under the RCP 6.0 scenario and 0.010 Ω/km^2 in the RCP 8.5 scenario, respectively (Table 5).

Generally, based on the value of current in corridors, the larger ecological resistance, the less ability for species migration or energy flow across these zones (Table 5). The ecological resistance in the corridors increased from 0.875 Ω/km^2 in 2020 to 0.885 Ω/km^2 in 2030, while the corridor current increased from 57,024 A to 57,048 A, which was affected by the size of the ecological sources under RCP 8.5. Compared with the RCP 2.6, RCP 6.0 and RCP 8.5 scenarios for 2020, when the average resistance of the corridors was the same, the average currents of the corridors under the RCP 6.0 scenario were 133 A and 43 A higher than that in the RCP 2.6 and RCP 8.5 scenarios, respectively. Meanwhile, there was an obvious change in the total corridor current with an increase of 58 A under the RCP 2.6 scenario. In comparison, the RCP 6.0 scenario decreased by 38 A from 2020 to 2030, and the change range of the total

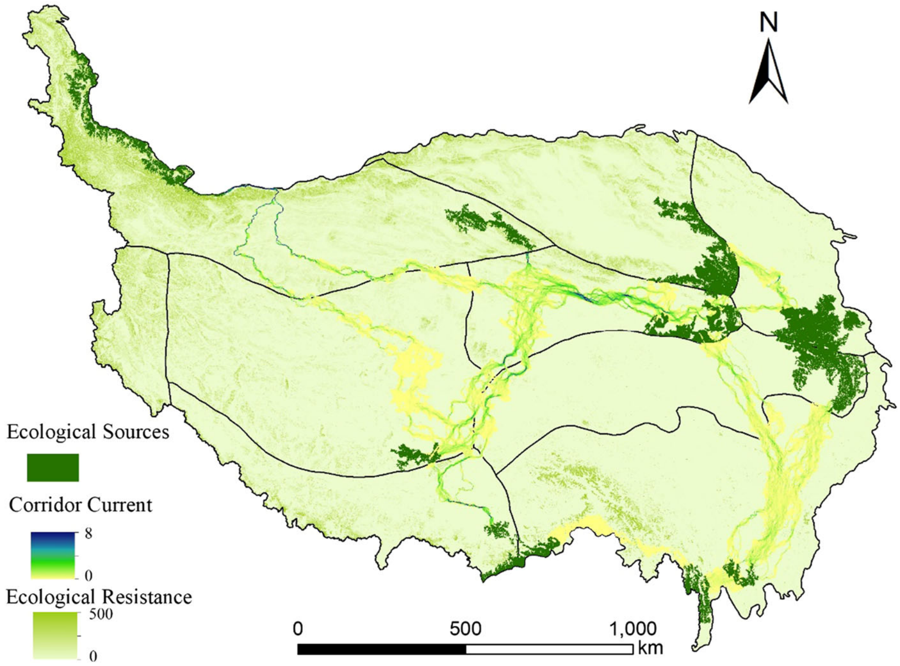

Fig. 6 The construction of the ESPs with circuit theory under the RCP 2.6 scenario in 2020

corridor current increased 24 A under the RCP 8.5 scenario. Moreover, the average current in the corridors exhibited little change in all scenarios.

Consequently, compared with the average ecological resistance and total/average current in the corridors, the most sustainable landscape pattern based on the ESPs was the RCP 8.5 scenario, the second was RCP 2.6, the third was RCP 6.0 and the last was RCP 4.5. Among them, the mainly reason for this result is that the area of grassland in RCP 8.5 scenario appeared obviously increasing more than in other scenarios. For example, the area of grassland increases by 5.5km^2 in RCP 8.5 in 2030 than in RCP 2.6 in 2030. Therefore, the expansion of grassland could improve the landscape sustainability under high carbon emissions (RCP8.5).

Discussion

The application of the ESPs with different geographical characteristics

ESPs are regarded as an effective method for strengthening the integrity of ecosystems by combining and arranging the relationship of the ecological processes and landscape services (Yu 1996). Based on the interactions between the patterns and processes, the ESPs represent connectivity and integrity from the perspective of the "source-corridor" framework at the landscape scale (Liu and Chang 2015). The "sources" within the ESPs could be regarded as the scattered landscapes in the region, and the "corridors" could be seen as the most convenient way to connect the decentralized landscapes (Vergnes et al. 2013; Dong et al. 2019). However, the distribution of the ecological sources would exhibit obvious regional differences owing to the obvious ecosystem diversity, which lead to the inappropriate landscape patterns with circuit theory. Therefore, it is an effective method to assign several thresholds for every natural source zone to better identify the ecological sources.

This method could also be applied to other places, such as outskirts. For example, the ecological intercorrelation in outskirts that possess various characteristics plays an essential role in the changes in environmental effects and energy use inefficiency in whole regions (Wang et al. 2017). The dramatic enhancement of human activities has led to the environmental quality of urban obviously lower than that of suburbs (Li et al. 2017). Thus, Montis et al. (2016) proposed urban–rural ecological networks to improve natural ecosystem quality and protect biodiversity, and the selection of core areas mainly adopted important natural areas. The approach of setting core areas with different thresholds was similar to the construction of the ESPs based on regional thresholds, which made landscape management at a large scale more flexible and practical.

The approach to achieving the sustainable landscape pattern

The sustainable landscape pattern could be seen as the key factor in the relationship among the landscape, the ecosystem and humans (Musacchio 2013; Lei et al. 2016; Abou-Dahab et al. 2019). At present, there are several approaches for creating sustainable landscapes (Bohnet et al. 2011; Antrop et al. 2013; Rode et al. 2019). According to the constraints of water resource capacity and the influence of future climate changes, Liu et al. (2019) adjusted the allocation of urban land use types to achieve a sustainable urban landscape. Nowak and Grunewald (2018) regulated landscape patterns based on the results of assessments with qualitative and quantitative landscape services. Xia et al. (2019) used the analytic network process (AHP) method to identify the key factors for sustainable rural landscape construction. These studies provided various indicators for understanding the sustainable landscape.

Based on typical landscape services (soil conservation, carbon sequestration, and habitat quality) and the landscape patterns in different future scenarios, this article used circuit theory to construct ESPs in the Qinghai-Tibet Plateau to assess the sustainable landscape patterns in the future. Accordingly, we chiefly proposed an integrative tool to assess the sustainability landscape pattern, which can provide spatially located quantitative guidance on optimizing the nature protection system in the Qinghai-Tibet Plateau. These mapped landscape elements should be regarded as an important supplement in the current nature protection system of the Qinghai-Tibet Plateau towards landscape sustainability. Moreover, this approach is also conductive to improving the landscape sustainability in nature reserves and national parks. For instance, the identified ecological sources can provide spatial explicit position in sustaining the landscape services; and the potential current paths can indicate the critical location in enhance landscape connectivity on an ecosystem service perspective. In addition, it is also conductive to recognizing the tendency of landscape sustainability through the parameters of ESPs under future predicted scenarios, which timely prevented the risk deriving from land use changes, and effectively took advantage of space for nature reserves and national parks.

Conclusion

The Qinghai-Tibet Plateau, an important geographical area in China, needs to provide essential maintenance of landscape sustainability. Based on future land use scenarios, this study assessed the landscape services in the Qinghai-Tibet Plateau and constructed its ESPs with circuit theory in different scenarios. We obtained the following main results. (1) The distribution of the landscape services on the Qinghai-Tibet Plateau was roughly high in the southeast and low in the northwest in every scenario. The total value variation of the three landscape services (soil conservation, carbon sequestration, and habitat quality) from 2020 to 2030 are relatively stable under RCP 6.0 and RCP 8.5 scenarios and relatively fluctuant under RCP 2.6 and RCP 4.5. (2) The ESPs contained 9 ecological sources and 16–17 ecological corridors in different scenarios. (3) The landscape service indicators combined with circuit theory showed the highest sustainability was under the RCP 8.5 scenario only under the appropriate scope of threshold, followed by RCP 2.6, RCP 6.0 was third and the last was RCP 4.5. Moreover, we proposed the management of the Qinghai-Tibet Plateau, which was the minimum protected area of 16,422 km^2 and 12,663 km^2 in the Kunlun Mountain desert zone and Qingnan Plateau wide valley alpine meadow grassland zone, respectively. By constructing the optimized ESPs in the regions with different scenarios, the method of this study, which contained several parameters, can contribute to providing a new methodology reference for assessing the sustainability of landscape patterns in the future.

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