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Spatio-Temporal Dynamics of Landscape Connectivity and Ecological Network Construction in Long Yangxia Basin at the Upper Yellow River

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Abstract: Analyzing multi-scale changes in landscape connectivity is an important way to study landscape ecological processes and also an important method to maintain regional biodiversity. In this study, graph-based connectivity was used to analyze the dynamics of the connectivity of natural habitats in the Long Yangxia basin of upper Yellow River valley from 1995 to 2015. We used the core areas of the nature reserves as the source regions to construct ecological networks under different thresholds, so as to identify key areas that can maintain overall landscape connectivity. The results showed that, from 1995 to 2015, the landscape connectivity in the study area increased for the first 10 years, and, since 2005, has declined. On a spatial scale, we found that both the connectivity of the ecological network and the length of the corridor increased with landscape resistance. Our analysis demonstrates the importance of the natural habitat in the southern part of the study area where connectivity was higher, as well as the sensitivity of connectivity of the northern area to human activities. Both large and medium patches contribute greatly to the overall landscape connectivity, while attention needs to be paid to the protection and management of small patches as they played "stepping stone" roles in maintaining and improving landscape connectivity. The proportions of landscape types that served as corridors, listed in order of their contribution to connectivity, were grassland, forestland, wetland and cultivated land. This suggests that, in addition to focusing on the protection of grassland and forest land, the reasonable planning and utilization of wetland and cultivated land will also have an impact on landscape connectivity. In addition, the protection of and improvement in habitats in the Sanjiangyuan Nature Reserve is of great significance to enhance landscape connectivity. Our study provides a scientific basis to support and improve regional landscape connectivity and biodiversity conservation over the next decade.

Keywords: landscape connectivity; ecological network; spatio-temporal dynamics; nature reserves; importance value of patch

1. Introduction

With socioeconomic development, the loss and fragmentation of natural habitats has become more and more serious due to human activities, which poses a serious threat to global biodiversity [1–3]. Maintaining and improving the landscape connectivity of natural habitats is an effective way to alleviate such issues at the regional scale [4]. Studies have shown that landscape connectivity has a significant impact on many ecological processes such as animal migration, plant seed diffusion, and regional species richness [5]. Therefore, assessing the change in landscape connectivity in a region, that is, dynamic landscape connectivity, is considered an important research in the field of biodiversity conservation [6].

Landscape connectivity is the role of landscape structure in promoting or hindering the diffusion and movement of ecological flows within a landscape, and reflects the responses of ecological processes to landscape pattern [7]. At present, landscape connectivity quantification methods are mainly based on ecological and mathematical theories such as composite population theory and spatial graph theory [8]. According to the method principles, they can be divided into percolation theory, distance model, graph theory, etc. [9]. Among them, the graph theory method is more and more widely used with the continuous development of graph theory index and the development and use of related software, such as Conefor Sensinode, Circuitscape, Guidos, Zonation and Marxan software [10,11].

Connectivity indices of graph theory can be divided into overall connectivity index and patch importance index according to their indicated information [10]. The overall connectivity index can reflect the regional connectivity level, while the patch importance index is used to indicate the size of a single patch in maintaining the regional landscape connectivity [8]. Therefore, the use of both landscape connectivity indices can support multi-scale analysis of local and overall connectivity of the landscape. However, existing research on landscape connectivity often focuses on the dynamics on temporal scales, and ignores the dynamic analysis across spatial scales.

The construction of ecological networks can effectively improve landscape connectivity through network optimization and corridors [12,13]. An ecological network is an open system that uses corridors to organically combine different ecosystems in the landscape and to form a network system that is closely connected in space and structure [13,14]. Among the many methods of constructing an ecological network, the minimum cumulative resistance model has been widely used in the construction of ecological networks in service of urban landscape planning and habitat protection [15]. The minimum cumulative resistance model was first proposed by Knaapen in 1992 [16]. This model is based on the cost of ecological flow moving between sources to minimize resistance, thereby identifying the minimum cost path in the current environment [17]. Therefore, the model can be used to construct ecological networks under different resistance thresholds, which can not only incorporate the spatial dynamics of landscape connectivity, but also identify the optimal path and provide targeted and scientific suggestions for optimizing the regional landscape connectivity [18].

Nature reserves, as the core areas of ecological networks, protect habitats for wildlife [19] and ecosystems and landscapes [20]. However, a series of ecological problems, such as land degradation and ecological corridor fragmentation caused by human activities and other factors, have reduced the landscape connectivity and directly or indirectly affected the actual protection efficacy of nature reserves within ecological networks [21]. However, a large body of research has demonstrated that nature reserves within ecological networks can strengthen ecological function and maintain regional ecological security [22,23].

In this study, we analyze the dynamic landscape connectivity of natural habitats in the upper reaches of the Yellow River in Qinghai province by using changes in landscape connectivity on temporal scale and minimum cumulative resistance model on spatial scale. The main objectives of this study are to: (1) analyze of the landscape connectivity dynamics of the study area and the patch importance from 1995 to 2015; (2) evaluate the ecological network of different resistance and distance thresholds based on human activities and natural conditions on the spatial scale; (3) identify important areas and target suggestions for landscape connectivity optimization. The results of this study can comprehensively reflect the change in dynamic landscape connectivity in Long Yangxia Basin and can provide a scientific reference for regional landscape management.

2. Materials and Methods

2.1. Study Area

Long Yangxia Basin is located in the upper reaches of the Yellow River in Gonghe County, Qinghai, China. It is the first gorge that enters the Yellow River Canyon after passing through the Qinghai grassland. It is also the location of the first large cascade power station in the upper reaches of the Yellow River. Therefore, it has not only unique geographical conditions, but also a very important impact on the ecological environment of the lower Yellow River [24]. The study area is located in the east of Hainan Tibetan Autonomous Prefecture in Qinghai Province (99°2′ E–103°48′ E, 33°54′ N–36°33′ N), which consists of fifteen counties with an area of 81,493 km^2 (Figure 1). The study area has a typical plateau continental climate, which is characterized by drought and less rain, long light time, strong solar radiation, and large daily temperature difference. The annual average temperature in the study area is 5.6 °C, and the maximum and minimum temperatures can reach 34 and −23.8 °C, respectively, with an average annual precipitation of about 550 mm.

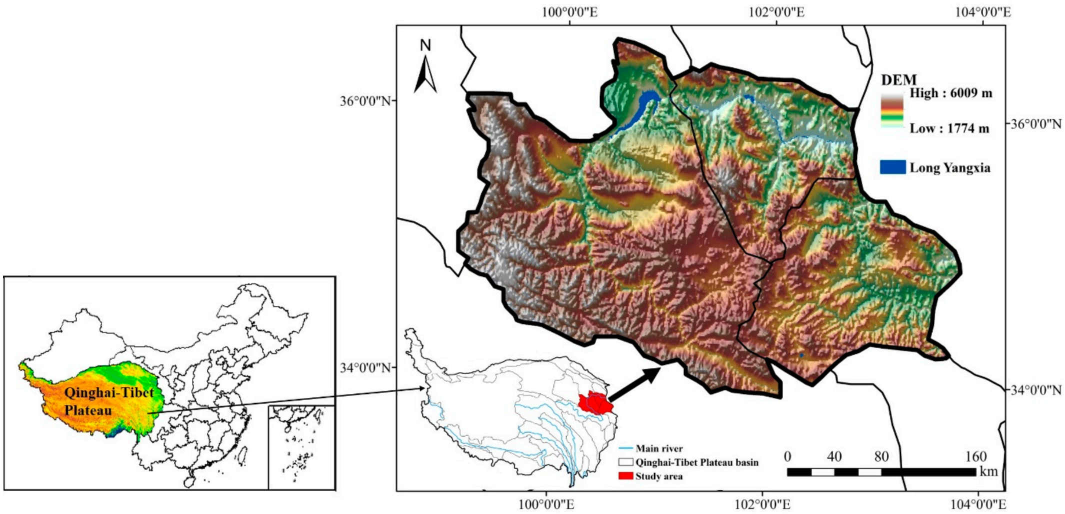

Figure 1. Spatial location of the study area.

Forests and grasslands are widely distributed in the study area, and there are five national nature reserves: Sanjiangyuan National Nature Reserve, Gahai-Zecha National Nature Reserve, Lianhuashan National Nature Reserve, Mengda National Nature Reserve and Taohe National Nature Reserve, areas rich in animal and plant resources and an important place for rare wildlife to inhabit and reproduce, such as Forest Musk Deer (*Moschus berezovskii*), Serow (*Capricornis sumatraensis*), Tibetan Crane (*Grus nigricollis*) and Tibetan gazelle (*Procapra picticaudata*). However, land desertification and soil erosion have intensified in the area [25], which has not only affected the local economic development, but also led to the continuous deterioration of the regional ecosystems, thereby affecting the biodiversity and the ecosystem stability.

2.2. Data Sources

In this study, to analyze landscape connectivity changes and construct ecological networks, we used five datasets and the data description and sources were displayed in Table 1. The human footprint dataset was downloaded from the Science Data Bank (http://www.sciencedb.cn/dataSet/handle/933), which directly provides the assigned and superimposed spatial data of human activities [26].

Table 1. Data description and sources. The human footprint dataset includes five spatial data representing human activities.

Data	Description	Data Source	Resolution	Time Periods
1. Human footprint dataset	Population density	Resource and Environment Data Cloud Platform http://www.resdc.cn/Default.aspx	1 km	2015
	Land cover data		1 km	2015
	Night light data	National Centers For Environmental Information, National Oceanic And Atmospheric Administration https://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html	1 km	2015
	Grazing density	Food and Agriculture Organization of the United Nations http://www.fao.org/ge\T1\textquoteleftonetwork/srv/en/main.home A Data Center in NASA's Earth Observing System Data and Information System https://sedac.ciesin.columbia.edu/	—	2006
	Railways and roads		—	2010, 2015
2. Ecosystem types	Spatio-temporal distribution of ecosystem types	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences http://www.resdc.cn/	1 km	1995, 2005, 2015
3. Nature reserve	Spatial distribution of nature reserves. Includes information on core areas of nature reserves	National Earth System Science Data Center http://www.geodata.cn/	—	2016
4. DEM (Digital Elevation Model)	Ground surface elevation	Resource and Environment Data Cloud Platform http://www.resdc.cn/Default.aspx	1 km	—
5. NDVI (Normalized Difference Vegetation Index)	Surface vegetation coverage		1 km	2015

2.3. Data Analysis

For our temporal analysis, we calculated a series of graph-based landscape connectivity indices to analyze the temporal dynamics in the connectivity of natural habitats, and the importance values of patches were calculated. In our spatial analysis, we combined the natural conditions and human activities, and used the core area of the nature reserves as ecological source regions to build ecological networks under different resistance thresholds; we also evaluated the importance of patch changes and corridor structure. Finally, we analyzed the spatio-temporal changes in landscape connectivity to identify key areas which play an important role in maintaining and improving landscape connectivity, and optimize the landscape structure. The schematic diagram of the study framework was shown in Figure 2.

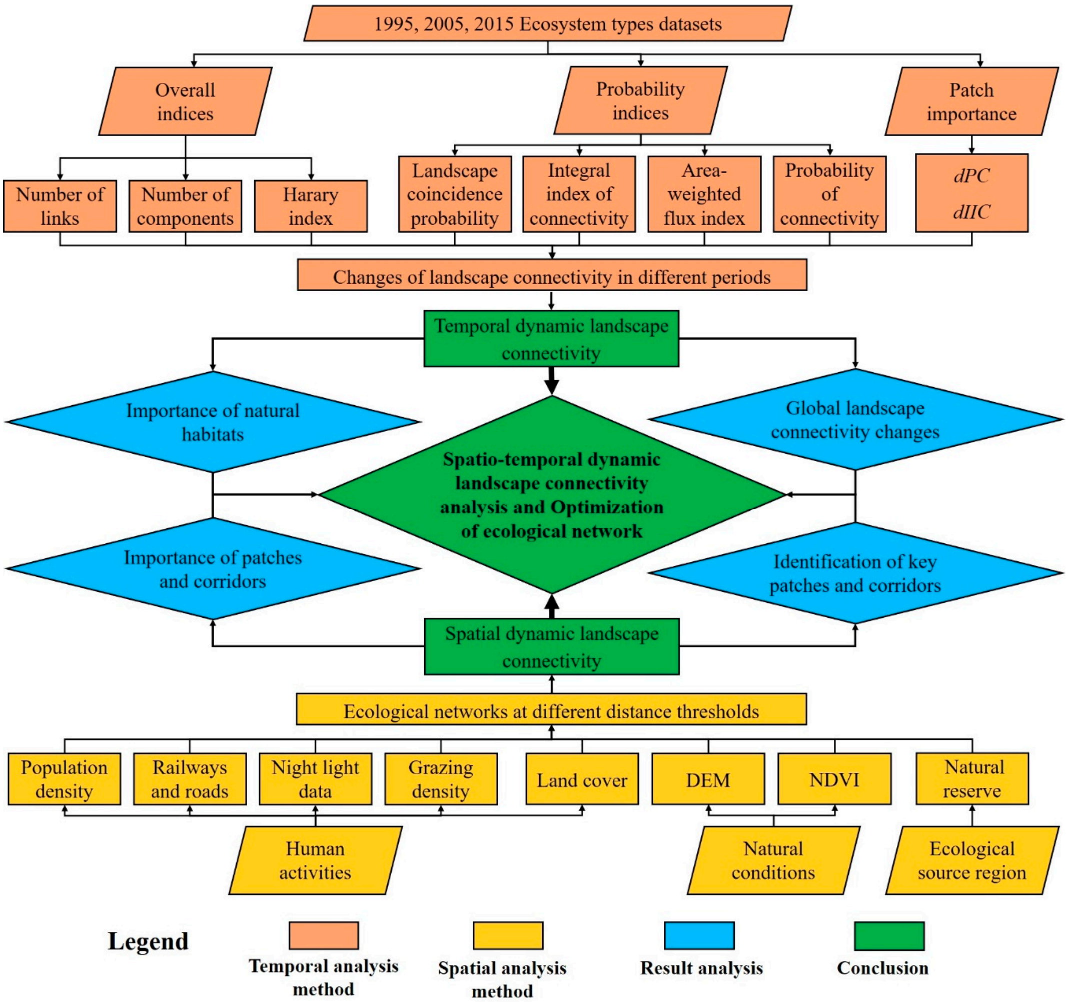

Figure 2. Schematic diagram of the study framework.

2.3.1. Global Landscape Connectivity Assessment

Landscape connectivity analysis based on graph theory can well reflect the interrelationship between species diffusion process and landscape structure [27]. It has been widely used in wildlife protection and regional spatial planning [28–30]. The graph-based global connectivity indices adopted in this study include number of links (NL), number of components (NC), H-Harary index (H), integral index of connectivity (IIC), area-weighted flux (AWF), probability of connectivity (PC) and landscape coincidence probability (LCP), which can reflect the landscape fragmentation process and identify important patches (Table 2). This study used the ecosystem type datasets in 1995, 2005 and 2015 to calculate the indices. The calculation of all indices was done by the Conefor Sensinode 2.6 software [31].

Table 2. Calculation formulas and descriptions of landscape connectivity indices.

Connectivity Index	Formula	Description and Interpretation
NL		Number of all connections between patches in the study area
NC		Number of landscape components divided by patches in the study area
H	$H = \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1,\, i\neq j}^{n}\frac{1}{nl_{ij}}$	n: Total number of patches in the study area; nl_{ij}: The minimum number of connections between patch i and patch j, $nl_{ij} = \infty$ between patches without connections; p_{ij}: Probability of direct diffusion pathway between patch i and patch j; p_{ijmax}: Maximum probability of each diffusion pathway between patch i and patch j; a_i, a_j: The area of patch i and patch j; A_L: The total area of the study area. The higher the connectivity of the study area, the greater the values of *H*, *IIC*, *AWF* and *PC*.
IIC	$IIC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{a_i \times a_j}{1+nl_{ij}}}{A_L^2}$	
AWF	$AWF = \sum_{i=1}^{n}\sum_{j=1,\, i\neq j}^{n} p_{ij} \times a_i \times a_j$	
PC	$PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} p_{ij} \times a_i \times a_j}{A_L^2}$	
LCP	$LCP = \sum_{i=1}^{NC}(C_i/A_L)^2$	C_i represents the total area of landscape components. When *LCP* = 1, it means that all landscape components in the study belong to the same type.

2.3.2. The Evaluation of the Importance of Natural Habitats

Important patches refer to habitat patches that have significant impact to the maintenance and improvement of landscape connectivity [32]. The patch importance value (*dI*) reflects the contribution of a patch to the overall connectivity of the landscape [33]. In this study, *dIIC* and *dPC* were used to calculate the importance of patches. The calculation formula is as follows

$$dI_k = \frac{I - I_{remove,k}}{I} \times 100\% \tag{1}$$

in which dI_k is the importance index of the patch k corresponding to the connectivity index I; I is the original connectivity index value of the study area; $I_{remove,k}$ is the connectivity index value of the study area after removing patch k. The larger the dI_k value, the higher the contribution of this patch to maintaining landscape connectivity.

2.3.3. The Construction of Ecological Network

Determination of Ecological Source Regions and Resistance Surface

The determination of the ecological source regions and resistance surface is an important step of constructing an ecological network [34,35]. According to the natural conditions of the Long Yangxia Basin, it is difficult to extract obvious boundaries for the natural habitats. As the starting point for species survival and diffusion, the ecological source regions play an important role in maintaining the ecosystem function [34]. Therefore, we used the ecosystem type datasets in 1995, 2005 and 2015, and selected the core areas of the Sanjiangyuan National Nature Reserve (S1, S2), Gahai-Zecha National Nature Reserve (G), Lianhuashan National Nature Reserve (L), Mengda National Nature Reserve (M) and Taohe National Nature Reserve (T) as the ecological source regions. We extracted a total of 12 source regions and numbered them (Figure 3). These regions are not only important places for the survival of animals and plants, but also important water conservation areas in the Qinghai-Tibet Plateau with abundant forest resources and water resources.

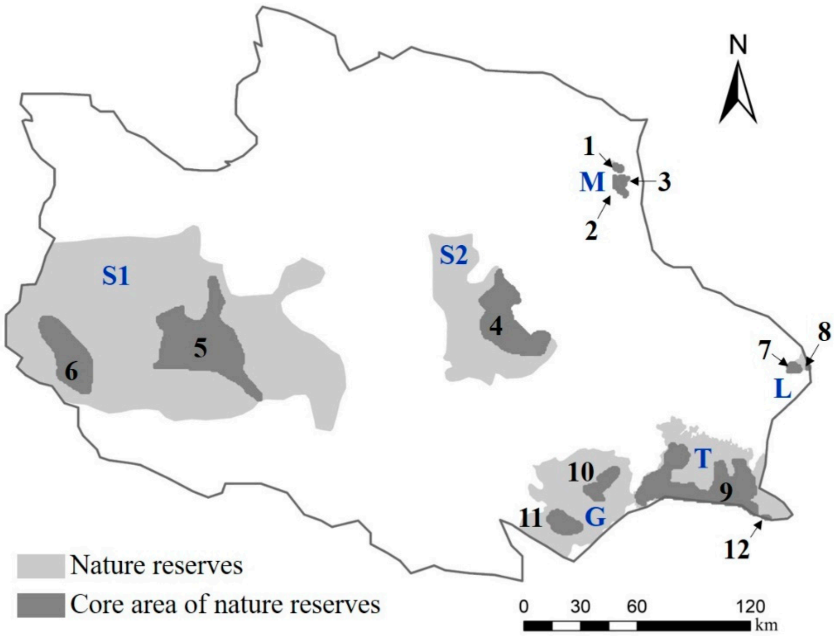

Figure 3. Distribution and number of ecological source regions. 1–12 represents the core areas of the Mengda National Nature Reserve (M), Sanjiangyuan National Nature Reserve (S2, S1), Lianhuashan National Nature Reserve (L), Taohe National Nature Reserve (T) and Gahai-Zecha National Nature Reserve (G), respectively. The source regions were used in the analysis of spatial dynamics in landscape connectivity.

Landscape resistance characterizes the difficulty of survival and movement of organisms within different land use types, i.e., the movement of species between different source regions needs to overcome landscape resistance. The higher the landscape suitability, the smaller the resistance to species movement. The resistance value is mainly affected by factors such as vegetation coverage, vegetation type, and human disturbance intensity. Different resistance assignments have a strong influence on a corridor's value [36]. Using previously collected data and research [26,37–39], we assigned values to eight factors of human activity and natural conditions. The human activities assignment directly used the data provided by the human footprint dataset (Table 3), and the natural condition factors are assigned according to the assignment criteria of the human activities (Table 4).

Table 3. Resistance assignment for human activities.

Resistance Layer	Classification Standard	Resistance Value
Population density	$pop_{score} = 2.21398 \times log(pop_{density} + 1)$ in which pop_{score} represents the re-assigned score of the grid, $pop_{density}$ represents the population density value of the grid.	0–10
Land cover	Built-up land	10
	Cultivated land and bare land	7
	Grassland	4
	Others	0
Grazing density	$grazing_{score} = 2.51531 \times log(grazing_{density} + 1)$ in which $grazing_{score}$ represents the re-assigned score of the grid, $grazing_{density}$ represents the grazing density value of the grid.	0–10
Night light	Digital Number = 0	0
	When Digital Number > 0, assign the value according to deciles.	1–10
Railways	Distance < 500 m	8
	Distance > 500 m	0
Roads	Distance < 500 m	10
	500 m < Distance < 1500 m	8
	1500 m < Distance < 2500 m	4

Table 4. Resistance assignment for natural conditions.

Resistance Layer	Classification Standard	Resistance Value	Resistance Layer	Classification Standard	Resistance Value
DEM	<3000 m	0	NDVI	>0.7	1
	3000 m–3500 m	2		0.4–0.7	3
	3500 m–4000 m	4		0.3–0.4	5
	4000 m–4500 m	8		0.1–0.3	7
	>4500 m	10		<0.1	9

Finally, the landscape resistance surface is obtained by superimposing the resistance layers based on ArcGIS 10.5, that is, the resistance value of each unit of the resistance surface is the sum of the resistance values of different resistance layers.

Minimum Cumulative Resistance Model

The minimum cumulative resistance model emphasizes the cumulative effect of landscape resistance at a certain spatial distance [29,40]. According to Knaapen [16] and Yu [41], the calculation formula is as follows

$$MCR = f_{min} \sum_{j=n}^{i=m} (D_{ij} \times R_i)$$

in which MCR is the minimum cumulative resistance value; R_i represents the resistance value of the space unit i; D_{ij} represents the distance from the source region j to a unit i in the landscape; f represents the positive function relationship between MCR and $(D_{ij} \times R_i)$. The smaller the MCR, the less resistance to the movement of the ecological flow. The Graphab software was used to construct an ecological network using minimum cumulative resistance model.

If the resistance experienced by an organism moving between source regions is less than or equal to the set resistance threshold, source regions will be connected. Conversely, if resistance is higher than the set resistance threshold, sources are not connected. Therefore, in order to explore the spatial dynamic of landscape connectivity, we referred to the relevant references [22,23] and then constructed ecological networks with resistance thresholds of 1000, 1500, 2000, 2500, 3000, 3500, and 4000, respectively, and calculated the length of corridor (least cost path) corresponding to the cumulative resistance (cost-weighted distance) by Graphab software, so as to explore the changes in landscape connectivity at different distance thresholds [42,43]. Different ecological processes occur at different scales, so the connection distances are also different. Even for a specific species diffusion or ecological flow movement, the appropriate threshold will change under different geographical and environmental conditions. Therefore, the analysis of ecological networks under different thresholds is also conducive to identifying key ecological patches and discovering weak parts of landscape connectivity, which can provide a reliable basis to identify the land needed to support landscape ecological security and the stability of regional ecosystems.

2.3.4. Analysis of Ecological Network Connectivity and the Importance of Patches and Corridors

In this study, *IIC* and class coincidence probability (*CCP)* were calculated to evaluate the overall landscape connectivity of the ecological network by Graphab software. *CCP* can represent the probability that two randomly selected patches in the habitat are connected to each other. When $CCP = 1$, all patches in the landscape can be connected. At the same time, we selected *dIIC* to evaluate the contribution of patches and potential corridors to maintain connectivity.

In order to compare the changes in the contribution of different patches to landscape connectivity, we used the natural break method to divide the patches into four size categories: large, medium, small, and extremely small. Moreover, we referred to the range of activities of organisms to establish buffer zones with a width of 2.5 and 5 km through the "Buffer" tools in the ArcGIS 10.5 [44–47], so as to analyze the landscape composition of potential ecological corridors under ideal ecological networks and evaluate the conservation efficiency of nature reserves.

3. Results

3.1. Temporal Dynamics of Landscape Connectivity

3.1.1. Changes in the Global Connectivity

It can be seen from Table 5 that the global connectivity showed an increasing trend from 1995 to 2005. *NL* and *NC* increased from 183 and 101 to 202 and 115, respectively. The values of *H*, *LCP*, *IIC*, *AWF* and *PC* all increased significantly, and their values almost doubled, indicating that the landscape connectivity of natural habitats and the range of species spread increased during this period. From 2005 to 2015, the increase in landscape connectivity slowed, and most of the indices remained stable, but we found that the *H* value dropped from 3233.95 to 2981.53, indicating that although the landscape structure did not change substantially, the potential connectivity of landscape decreased. In general, the highest values of *LCP* and *IIC* were 0.38 and 0.117, indicating that the connectivity of natural habitats in the study area was poor. From the change in *H* value, we found that the potential connectivity of the natural habitat decreased, and the landscape had a tendency to fragment.

Table 5. Global landscape connectivity in different periods. *NL*, *NC* and *H* represent overall connectivity, *IIC*, *AWF*, *PC* and *LCP* represent probability connectivity.

Connectivity Indices	1995	2005	2015
Number of links (NL)	183	202	204
Number of components (NC)	101	115	118
H-Harary index (H)	1736.71	3233.95	2981.53
Integral index of connectivity (IIC)	0.059	0.117	0.117
Area-weighted flux (AWF)	14,709,300	22,172,950	23,356,630
Probability of connectivity (PC)	0.22	0.39	0.41
Landscape coincidence probability (LCP)	0.19	0.37	0.38

3.1.2. Changes in the Importance of Natural Habitats

Figure 4 shows that the importance value of patches in the southern part of the study area is relatively high, which may be related to the widely distributed forest land and grassland in these areas. In the north-western region, the importance values of patches did not change significantly in the two periods, but we found that the *dPC* was higher than *dIIC*, indicating that although the landscape structure of the natural habitat is poor, the patches in the north-western region have a potential contribution to connectivity, which plays an important role in improving the connectivity of the landscape.

The most obvious change with time is exhibited in the north-eastern part of the study area, where the importance of patches increased significantly between 1995 and 2005, but decreased from 2005 to 2015. The north-eastern region is located in Long Yangxia downstream and is a region with intense human activity, which may be the cause of the large change in patch importance value in this area.

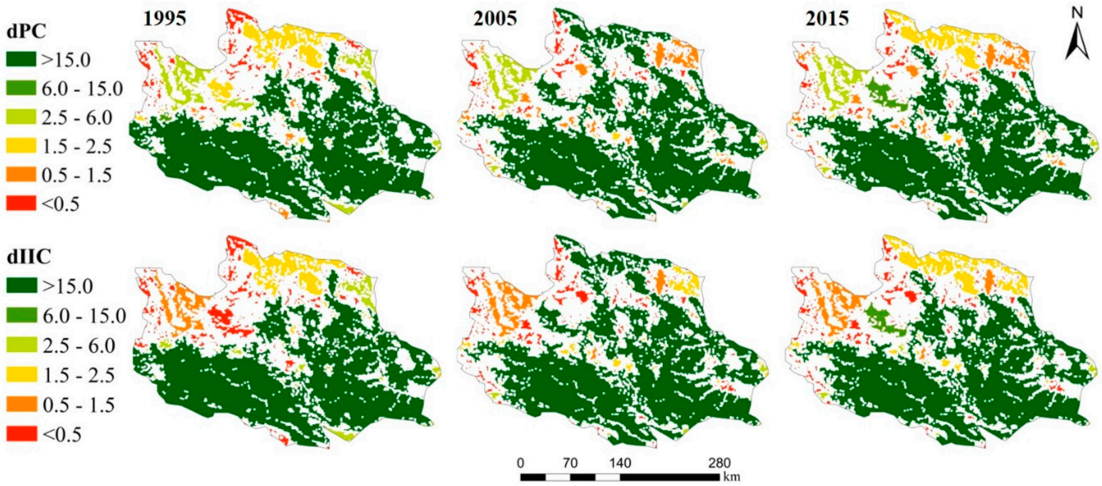

Figure 4. The important levels of natural habitats in different periods. *dPC* and *dIIC* represent the importance of patches calculated by probability of connectivity (PC) and integral index of connectivity (IIC), respectively.

3.2. Spatial Dynamics in Landscape Connectivity

3.2.1. Construction of Ecological Network under Different Distance Thresholds

We analyzed the changes in *CCP* and *IIC* under different resistance thresholds. From Figure 5, we can see that the values of *CCP* and *IIC* increase with the increase in the threshold, and reach the maximum when the resistance threshold is 3500. When the resistance threshold is between 1500–2000, there is a small increase in connectivity. The maximum growth rate of connectivity is between 2500 and 3000, indicating that this resistance threshold changes have a significant impact on biological diffusion and landscape connectivity.

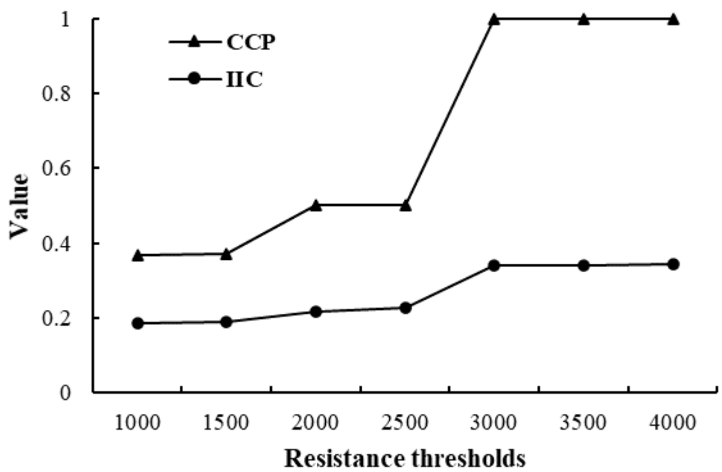

Figure 5. Integral index of connectivity (IIC) and class coincidence probability (CCP) in different resistance thresholds.

Through the construction of the ideal ecological network to ensure all ecological sources are connected, a total of 16 corridors were obtained. In order to intuitively express the relationship between corridor resistance and length, we calculated the cost-weighted distance (CWD) and least cost path (LCP) of corridors (Table 6). The shortest corridor length is 1883.09 m, and the longest corridor length is 18,254.53 m. The length of the corridors increases with increasing resistance thresholds. Combined with the results of Figure 5, we found that when the cumulative resistance of the corridor is greater than 2500, the length of the corridor increased significantly from 91 to 130 km. The increase in these long-distance corridors promotes the connectivity of the landscape; although the identification of these corridors did not contribute to the activities of small animals within the habitat, it is of great significance to some wild animals with long-distance migration habits. Combining with the results of Figure 5 and Table 6 also shows that the analysis of landscape connectivity under different thresholds is essential for identifying key corridors.

Table 6. Resistance and distance of potential corridors under ideal conditions, while CWD represents the cumulative resistance of corridors. LCP represents the length of corridors.

Corridors	CWD	LCP (m)	Corridors	CWD	LCP (m)
3-2	24.14	1883.09	4-2	1841.83	80,225.19
8-7	58.52	4223.09	10-4	1876.96	77,963.59
12-9	84.8	4546.17	9-4	2021.77	88,403.71
2-1	85	3120	11-4	2115.95	97,163.46
10-9	292.2	15,443.21	5-4	2794.84	135,360.5
11-10	345.99	16,546.3	7-2	2808.56	148,440.75
6-5	911.33	37,227.78	7-4	2844.93	147,817.54
9-7	1131.88	58,241.86	11-5	3748.28	182,548.53

3.2.2. Analysis of the Importance of Patches and Corridors

We calculated the *dIIC* of patches and corridors and visualized the ecological network (Figure 6). It can be found that the number of corridors increases with the increase in the resistance threshold, and the importance values of corridors also change. The importance values of corridors between nature reserves increased, such as corridor 5-4 and corridor 9-4, while the importance values of corridors within nature reserves decreased, such as corridor 10-9, and corridor 11-10. When the resistance threshold reaches 4000, the ecological network reaches an ideal state. The corridors of the ideal ecological network are mainly distributed in the middle and southeast of the study area. There are few corridors available in the northern area, which may be affected by the fragmentation of the natural habitat in the northern area.

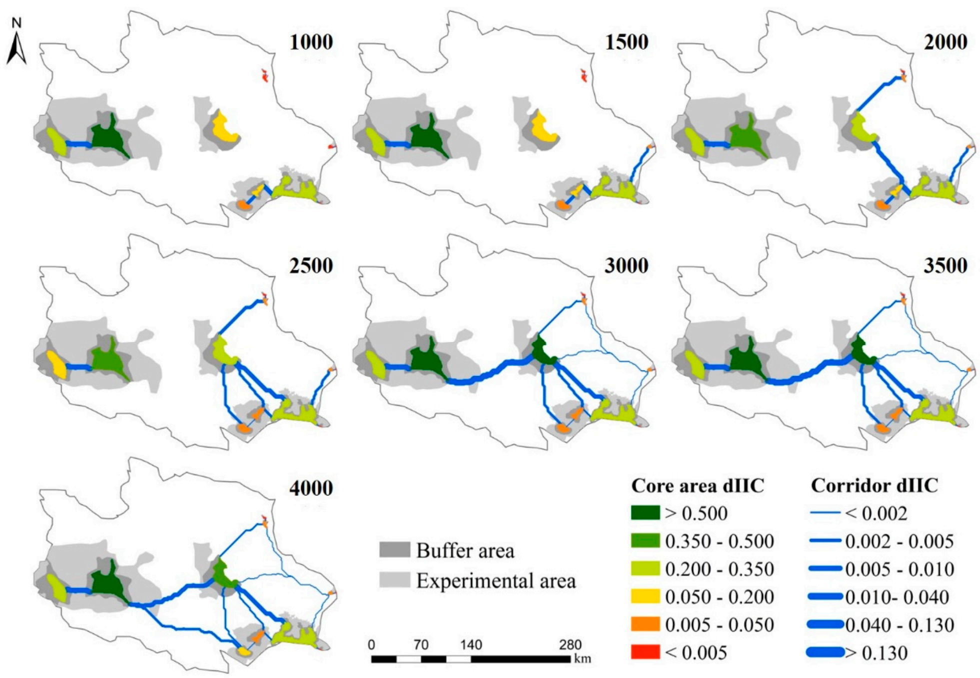

Figure 6. Ecological networks under different resistance thresholds. *dIIC* represents the importance of patches and corridors calculated by integral index of connectivity (IIC).

Through the analysis of the ecological network structure, we found that when the resistance threshold is 1500, patch 4 is an independent patch, and when the threshold rises to 2000, it can play the role of a "stepping stone" patch to connect the other two sources and increase. The overall connectivity of the ecological network. When the threshold increased from 2500 to 3000, that is, corridors with a threshold greater than 100 km are identified, patch 4 and patch 5 were connected and their importance values increased significantly, which further increases the connectivity, a result that is consistent with our findings about the impact of resistance thresholds on connectivity (Figure 5).

Figure 7 illustrates that the importance values of large and medium patches did not change significantly with the increase in threshold, and the importance values of some patches even decreased, such as patch 4. The importance value of patch 10 had a significant increase at the threshold of 2000, which is likely related to its location at the junction of two nature reserves. The importance values of small patches and extremely small patches increased obviously with the increase in threshold, indicating that their contribution to landscape connectivity had increased.

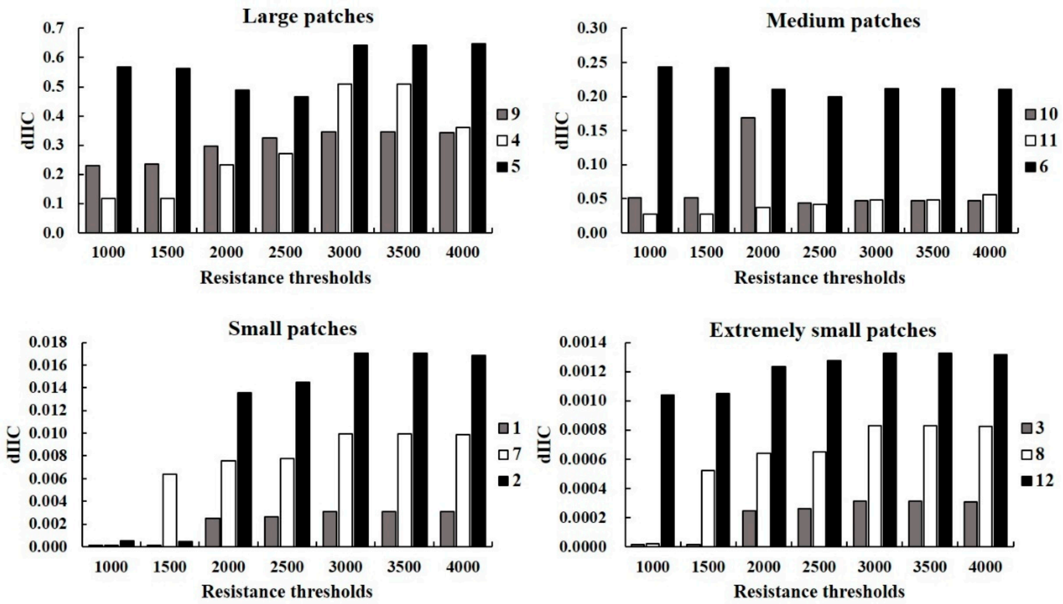

Figure 7. Comparison of the importance of ecological source areas. 1–12 represents the core areas of the Mengda National Nature Reserve (M), Sanjiangyuan National Nature Reserve (S2, S1), Lianhuashan National Nature Reserve (L), Taohe National Nature Reserve (T) and Gahai-ZechaNational Nature Reserve (G), respectively. *dIIC* represents the importance of patches calculated by integral index of connectivity (IIC).

3.3. Analysis of Buffer Zone of Potential Ecological Corridor

The analysis of the landscape composition of potential corridors can improve and optimize the landscape more purposefully. Table 7 shows that grassland is the main landscape type that constitutes corridors, accounting for about 60% of the total area of potential ecological corridors, and forest land accounts for about 25%. It can be seen that in the landscape, natural forest land and grassland play a major role in species diffusion. We found that wetland and cultivated land were also represented in corridors, indicating that they may have an indirect impact on biological activities in natural habitats.

Table 7. Percentage of different ecosystem types in 2.5 and 5.0 km corridor buffer zones.

Ecosystem Types	2.5 km Buffer Zone (%)			5.0 km Buffer Zone (%)		
	1995	2005	2015	1995	2005	2015
Farmland ecosystem	2.95	3.45	3.38	3.40	3.76	3.74
Forest ecosystem	28.36	28.67	28.81	26.94	26.65	26.67
Grassland ecosystem	63.41	61.47	61.37	63.61	62.47	62.46
Water and wetland ecosystem	4.07	4.20	4.17	4.17	4.29	4.25
Settlement ecosystem	0.14	0.18	0.20	0.14	0.24	0.32
Desert ecosystem	0.33	1.40	1.42	0.47	1.58	1.56
Other ecosystems	0.74	0.64	0.65	1.27	1.00	1.01

Over time, the proportion of grassland ecosystems decreased, and the proportions of desert ecosystem and settlement ecosystem increased. Although the proportion of settlement and desert is not large, these types of land use have an obvious barrier to species movement and landscape connection. Therefore, attention should be paid to these areas to avoid damage to the existing corridors.

We analyzed the distribution of corridors in nature reserves to evaluate the protection efficiency of nature reserves (Table 8). The area of corridor in Lianhuashan Nature Reserve is the largest, which indicates that it can provide a better place for the survival and activities of animals. When the buffer zone width is 5 km, 87.92% of the corridor falls within the Lianhuashan Nature Reserve, which means that this nature reserve can also effectively protect wide-ranging organisms. The percentage ofpotential corridors in Sanjiangyuan Nature Reserve and Taohe Nature Reserve is small, indicating that the natural habitats of these reserves are not well protected. Especially for Sanjiangyuan Nature Reserve, although it occupies a large area, it does not provide good conditions for the movement and migration of animals.

Table 8. Percentage of potential corridors in nature reserves. Sanjiangyuan National Nature Reserve (S1, S2), Gahai-Zecha National Nature Reserve (G), Lianhuashan National Nature Reserve (L), Mengda National Nature Reserve (M), Taohe National Nature Reserve (T).

Nature Reserves	Area of Nature Reserves (km^2)	2.5 km Buffer Zone		5.0 km Buffer Zone	
		Area of Corridors (km^2)	Percentage	Area of Corridors (km^2)	Percentage
L	75	34	45.64	66	87.92
M	232	59	25.42	85	36.47
T	2252	134	5.95	261	11.60
G	2310	349	15.09	722	31.24
S1	2960	396	13.36	887	29.95
S2	12,875	311	2.42	661	5.13

4. Discussion

4.1. Spatio-Temporal Dynamic Landscape Connectivity Analysis

In this study, we used the graph theory method to analyze the spatial and temporal changes of landscape connectivity. Our temporal results showed that the global connectivity of the landscape in the study area increased greatly from 1995 to 2005. In the 1990s, the ecological quality of Long Yangxia basin was deteriorating. The soil erosion and desertification not only caused damage to natural habitats, but also caused heavy losses to local agriculture and animal husbandry, which had a great impact on ecosystems and people's lives [48]. Therefore, as people began to realize the importance of ecological protection, a series of measures, such as mountain closure and afforestation, and increased protection of natural grasslands, were enacted. These measures were effective measures, to a certain extent, for curbing grassland degradation and land desertification. However, due to the climatic conditions of the plateau and the impact of human activities, the ecological degradation in the area is still quite serious. As a result, the landscape connectivity has declined in some areas, a finding supported by published studies that have also shown that land use can affect agro-pastoral production and ecosystems, but cannot fundamentally solve ecological problems [49]. Our results suggest that more effective and targeted methods are needed to control soil erosion and alleviate grassland degradation, and the task of improving the ecological environment remains critical.

Ahern and Opdam et al. [50,51] found that spatial analysis of landscape connectivity and identification potential corridors based on changes in thresholds are critical in maintaining the species diversity, a finding also confirmed in our research. When the resistance threshold is small, the landscape connectivity of the ecological network is low, and there are no corridors among the nature reserves, but the corridors inside the reserve play an important role, by providing a suitable habitat for some small and medium-sized animals. With the increase in the resistance threshold, we found that when the threshold is greater than 2500, potential corridors with a length greater than 100 km were identified, accompanied by a significant increase in the landscape connectivity of the ecological network. Some studies focus on the corridors of short-range moving animals, but ignore the movement range and paths of the long-distance migration animals [52–54]. In fact, these long-distance corridors may not have much effect on small organisms, but there are some animals with migration habits, such as Wild Yaks (*Bos mutus*) and Tibetan Antelope (*Pantholops hodgsonii*), which need long-distance migration for foraging and reproduction, and their migration distance can reach up to 400 km [55]. Therefore, we believe that the identification and protection of some long-distance corridors is of great importance. In addition, non-contiguous or non-proximal habitat distribution will lead to the decline in landscape connectivity. By identifying corridors under different resistance thresholds, the landscape structure can be effectively optimized, which not only promotes the circulation of organisms, but also maintains the stability of the ecosystem.

In future studies, the optimal distance threshold can be determined based on specific species or populations, combined with the distribution characteristics of organisms to provide strategies for the protection of specific species [26,40,56].

4.2. Identification of Key Areas and Optimization of Landscape Pattern

Through the construction of ecological network and the analysis of patch importance, it is helpful to determine the key areas and identify important nodes in the connected landscape [41,57]. The ecological nodes are regions with key ecological roles in the landscape, which play the role of a "stepping stone" in ecological networks [35]. Our results indicated that the importance values of natural habitats downstream of Long Yangxia basin exhibited fluctuations with time. Due to the construction of hydropower stations and tributary roads, the natural habitats in the north of the study area were disturbed more and more frequently, and the resulting landscape fragmentation is the main reason for the change in landscape connectivity. Therefore, the impact on the ecosystems should be taken into account with major engineering projects and utilization. The identification and establishment of nodes can not only provide a resting place for long-distance species migration, but also enhance the ecological function of the overall landscape. For example, the overall connectivity of the northwest of the study area is poor, but the possible connectivity is better, which can reflect the changes within the landscape, indicating that this area has a potential "stepping stone" role and has a great value of protection. In addition, the corridors in the southeast of the study area are densely distributed, so some new protected areas can be established to improve the landscape connectivity and optimize the overall structure of the ecological network [58].

In general, the importance of patches in the south of the study area is high and stable, and more attention needs to be paid to the protection of natural habitats in the northern area. The Sanjiangyuan Nature Reserve in the middle of the study area is not important for small-scale biological activities, but as the threshold increases, it becomes an essential "stepping stone" patch to maintain overall landscape connectivity. Studies have shown that the patch importance value increases with the patch area, but the contribution of patches to landscape connectivity is also affected by the distance threshold [59], which is consistent with our findings. In addition, there are few potential corridors in Sanjiangyuan Nature Reserve, so attention should be paid to the protection of natural habitats and the construction of corridors.

We found that large and medium-sized patches play an important role in maintaining overall landscape connectivity, while small patches have a "stepping stone" effect on the establishment of corridors in small areas. Therefore, the importance of patches for connectivity is also related to the distance and connectivity between patches. In the optimization of ecological networks, we must pay more attention to the role of small patches. For instance, some small "stepping stone" patches can be maintained or reconstructed around large resource patches to improve the landscape connectivity. An et al. found that the overall connectivity of the landscape improved significantly after constructing the "stepping stone" patches through model simulation, and confirmed the important role of small patches in improving the landscape structure [60].

In addition, adjusting the corridor composition can also optimize the landscape pattern, especially the rational utilization of wetlands and cultivated land. The nature reserve is not only a habitat for many rare wild animals and plants, but also has abundant natural resources. All the nature reserves in the study area are important water conservation areas on the Qinghai-Tibet Plateau, and play an extremely important ecological function in the ecosystem. It is recommended to strengthen the protection of wetlands while maintaining and increasing nature reserves, and attach importance to the material exchange and functional connection of natural wetlands [59,61].

For cultivated land, some studies have shown that using agricultural landscapes as "steppingstone" patches not only provides food for human communities, but also provides breeding grounds and shelters for wildlife [62,63]. On the other hand, the movement of organisms in different patches can have a positive impact on grasslands and cultivated lands. Walking and trampling by animals can promote soil movement, which can help cover and spread plant seeds and increase grassland vegetation regeneration ability. At the same time, moderate treading can accelerate the decomposition of organic matter, increase soil water retention capacity, and improve the living conditions of plants. In addition, landscape heterogeneity can be incorporated into spatial planning to improve ecological function and biodiversity protection [64]. For example, some regions have adopted an ecological agriculture model of crop and forage rotation [65]. This new model not only optimizes the landscape structure, but also allows farmers to participate in landscape management, thus achieving the unification of economic development and environmental protection [66].

5. Conclusions

This study analyzed the spatio-temporal changes in landscape connectivity using graph theory, and explored changes in patch importance and corridor structure, so as to put forward targeted optimization suggestions for landscape structure. Our results showed that the landscape connectivity in the Long Yangxia basin increased from 1995 to 2005. From 2005 to 2015, the landscape structure of the study area varied little, but the potential connectivity decreased. By constructing ecological networks with different thresholds, we found that the landscape connectivity increased with the increase in the threshold, and the importance of long-distance corridors gradually emerges. Patches of different sizes have different effects on landscape connectivity. Large and medium patches play a major role in maintaining the overall connectivity of the landscape, such as the Sanjiangyuan Nature Reserve, while small patches, such as the Gahai-Zecha Nature Reserve, are used as "stepping stone" to improve connectivity in local areas.

In an ideal ecological network, nature reserves or protected areas serve key roles in maintaining and supporting connectivity. However, in the upper reaches of the Yellow River, with the exception of the Lianhuashan Nature Reserve, the protection efficiency of the other four nature reserves was low, even for the Sanjiangyuan Nature Reserve, the largest reserve. This highlights the need to improve and strengthen and establish new corridors. We also found that wetland and cultivated land are small but important parts of corridor composition. This finding points to the importance of "stepping stone" patches, and the need for wetland protection and the enhancement of landscape heterogeneity in cultivated land. Our research provides theoretical guidance for improving landscape connectivity and optimizing ecological networks.

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