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Relationship between Topological Structure and Ecosystem Services of Forest Grass Ecospatial Network in China

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Abstract: Forest and grass ecological space is the key component of the ecosystem and plays a vital role in regulating the carbon, water, and energy cycle. The long-term exploitation of forest and grass ecological space and huge population pressure have gradually degraded the function of China's ecosystem. Therefore, forest and grass ecological space plays an important role in maintaining the stability of the ecosystem. The relationship between forest and grass ecospatial network structure and ecosystem service has been the focus of research. In this study, the forest and grass ecospatial network is constructed based on the minimum cumulative resistance (MCR) model. Then, the topological indicators (degree, weight clustering coefficient, node weight, unit weight, weight distribution difference, betweenness, PageRank) of the forest and grass ecospatial network were calculated by combining the complex network theory to analyze the relationship between these topological indicators and the three ecosystems (water retention, soil conservation, carbon storage). Based on the ecological significance of topological indicators, we identified ecologically fragile areas and proposed areas and directions for optimizing the ecospatial structure. Results show that the spatial distribution of the three ecosystem services in the southeast region of China is higher than that in the northwest region of China and shows a gradual decrease from the east to the west. The degree, node weight, unit weight, PageRank, and betweenness were highly significant and positively correlated with the three ecosystem services, among which PageRank had the highest correlation with water retention ($p < 0.01$, $R^2 = 0.835$). Based on the spatial distribution characteristics of the different topological indicators, the quantitative relationship between the structural characteristics of the forest and grass ecospatial network and ecosystem services is clarified, revealing the intrinsic connection between ecological processes and ecosystem services. Through rational optimization of the forest and grass ecospatial network, ecosystem services can be effectively improved and ecosystem stability can be enhanced.

Keywords: national scale; forest and grass ecospatial network; ecosystem service; complex network; topological features

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1. Introduction

Forest and grass ecological space is the largest ecosystem on land and plays a vital role in maintaining the stability of the biosphere, global climate stability, and ecological balance [1,2]. In recent decades, with the global economic development, population growth and high consumption of natural resources [3], the continuous disturbance of human activities has led to rapid changes in global land cover, resulting in a continuous reduction in the area of forest and grass ecosystem space and increasing fragmentation of patches, which has seriously affected the functions of material cycling, energy flow and information transmission in ecosystem services [4]. Therefore, the current ecosystem is facing a serious threat. The loss and degradation of ecosystem services will have an important impact on human security and health and directly threaten regional and even global ecological security [5].

In recent years, China has made considerable efforts to improve ecosystem services, for instance, by implementing such measures as the Grain for Green Program Intensifies, the three-north shelter forest program, two barriers and three belts [3,6]; different ecosystems are connected to each other to constitute a forest and grass ecospatial network [7]. By increasing ecological sources (Grain for Green Program Intensifies) and ecological corridors (the three-north shelter forest program), the spatial pattern distribution of the ecological landscape is changed, which improves the connectivity of the overall forest and grass ecospatial network and enhances the transmission of energy flow between ecological corridors [8]. Energy flow and information transfer in the forest and grass ecospatial network were significantly improved, and the resistance stability of the ecosystem was enhanced [9,10]. Therefore, this paper explores the effects of different topological indicators on ecosystem services, which are based on the structural characteristics of forest and grass ecospatial networks. This study is important for maintaining the stability of China's ecosystems.

The ecospatial network is structured in the "patch–corridor–matrix" model, and the spatial combination of ecological sources and ecological corridors is the basis of the ecospatial network [11]. According to the ecological importance, Getis-Ord GI*, ecological suitability, and other indicators, ecological sources were selected [12–14], key ecological elements were identified, and MCR was used to better model the potential trends of ecological flow space movement [15]. In previous several studies, researchers explored the effects of different landscape pattern aggregation and dispersion degrees on ecological flow transport at spatial scales through landscape pattern indices [16] or analyzed the effects of landscape factors such as landscape fragmentation on ecosystem stability based on ecological network risk indices [17]. In addition, some scholars objectively analyzed the spatial trends of ecological environmental quality based on remote sensing ecological indices [18]. However, different landscape indices mainly focus on describing the spatial location distribution of ecological landscapes, and it is difficult to measure the quantitative relationship between the spatial pattern distribution of landscape patches and ecosystems. In addition, the topological indices based on the complex network theory can well represent the relative spatial relationship between features and abstract the ecological source and ecological corridor in the ecospatial network into points and lines in the complex system [19]. Through the topological index of a complex network, the overall structure of the ecospatial network system is quantified, and the relationship between different topological indices and ecosystem services is explored. This theoretical approach provides a new way to explore the relationship between changes in ecospatial network patterns and ecosystem services.

Complex networks are large-scale networks with complex topology and dynamical behavior, constructed of several nodes interconnected by edges [20], which are widely used in the study of sociology, physics, biology, geography, and other disciplines [21,22]. The complex network is a characteristic network based on the theory of a complex system, and complex system is a set formed by the cooperation and connection of multiple parts [20]. The connection between the structure and function of a complex system is studied, which is quantitatively reflected through static index features such as degree, average path length, and clustering coefficient [23]. The ecospatial network is an integrated, dynamic, and open system, which is a complex network composed of landscape patches and ecological corridors, with unique spatial structure characteristics [24]. Ecospatial network structure characteristics can reflect the importance, independence, aggregation, connectivity, and complexity of ecological sources. Its core function is to analyze the laws and characteristics of energy flow in ecospatial networks [25]. Therefore, the characteristic parameters in the complex network are used to characterize the specific ecological processes of the ecospatial network, to better reflect the ecological processes of material, energy, and information flow transmission in the forest and grass ecospatial network.

Purpose of this study: (i) analysis of changes in spatial pattern of ecosystem services (water retention, soil conservation, carbon storage) in China in 2020; (ii) construct the 2020

China forest and grass ecospatial network and study the spatial distribution characteristics of topological indicators of the forest and grass ecospatial network. (iii) This paper discusses the relationship between ecosystem services and the structural characteristics of the forest and grass ecospatial network. According to the ecological significance of different topological indicators of the forest and grass ecospatial network, the corresponding optimization strategies for the forest and grass ecospatial network in China are proposed.

2. Materials

2.1. Study Area

China is located in the eastern part of Asia and on the west coast of the Pacific Ocean. It has a land area of 9.6 million square kilometers, a land border of more than 20,000 km, a territorial sea consisting of the Bohai Sea (Inland Sea) and three major border seas, the Yellow Sea, the East China Sea, and the South China Sea, and a continental coastline of 18,000 km in the east and south. China is a vast country with a complex and diverse terrain, with a high topography in the west and a low topography in the east. Among them, mountains, plateaus and hills account for about 67% of the land area, while basins and plains account for about 33% of the land area. The topography and climate types are complex and diverse, resulting in a relatively rich variety of vegetation and complex distribution. This study focuses on analyzing the relationship between the topology of forest and grass ecological spatial networks and ecosystem services, and revealing the intrinsic link between ecological processes and ecosystem services. In this paper, the mainland China region is taken as the study area (Figure 1).

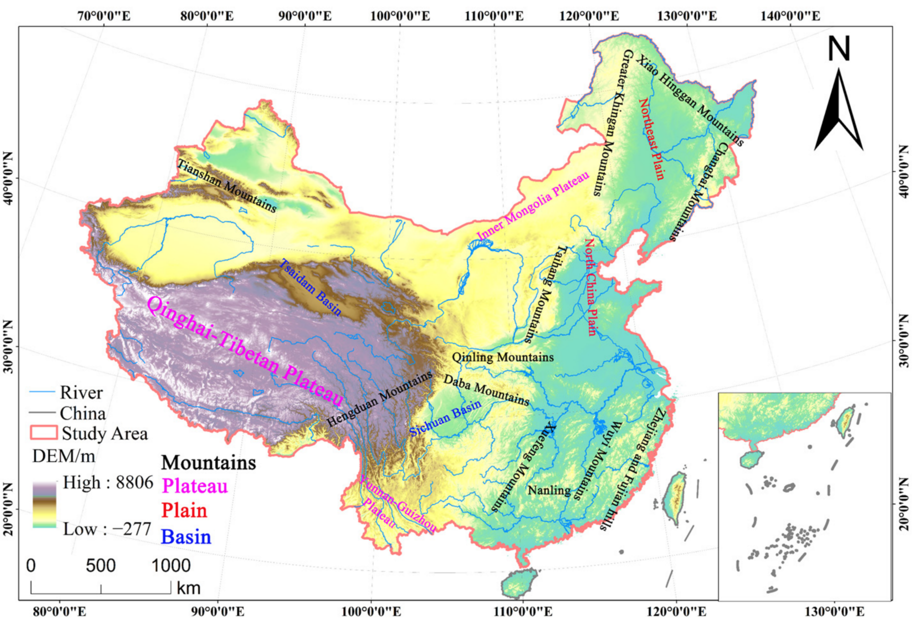

Figure 1. The geographic location of the study area.

2.2. Data Sources and Descriptions

In this study, we used a variety of data products. For example, land use data, Landsat data, MODIS data, soil data, digital elevation data, meteorology and other basic data were used to calculate three different ecosystem services and the construction of a forest and grass ecospatial network. The data sources and descriptions are shown in Table 1.

Table 1. List of data.

Data	Data Formats	Data Description	Data Sources	Data Time Resolution and Coverage
Study area boundary	Shapefile	China Vector Boundary	Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/, accessed on 16 April 2022)	2020 (China Mainland)
Land use	Raster (30 m)	Land use interpreted from Landsat 8	Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/, accessed on 16 April 2022)	2020 (China Mainland)
Normalized Difference Vegetation Index (NDVI)/(Normalized Difference Water Index) NDWI	Raster (30 m)	Landsat 8 and calculations (Including monthly NDVI, NDW and annual NDVI, NDWI)	Google Earth Engine (http://code.earthengine.google.com/, accessed on 16 April 2022)	Monthly average value in 2020 and average maximum value in 2020 (China Mainland)
Net Primary Productivity (NPP)	Raster (500 m)	MOD17A3H database	Google Earth Engine (http://code.earthengine.google.com/, accessed on 16 April 2022)	2020 (China Mainland)
Road Network Data/Water Network Data	shapefile	Open Street Map (Road, Water line)	(http://www.openstreetmap.org/, accessed on 16 April 2022)	2020 (China Mainland)
Digital Elevation Model (DEM)	Raster (30 m)	Elevation data	Geospatial Data Cloud (https://www.gscloud.cn, accessed on 16 April 2022)	2020 (China Mainland)
Meteorological data	Raster (1 km)	Including monthly average precipitation and annual precipitation, and potential evapotranspiration	National Earth System Science Data Center (http://www.geodata.cn/, accessed on 16 April 2022)	Monthly average value in 2020 and average value in 2020 (China Mainland)
Soil data	Raster (1 km)	Soil type Soil texture (Sand, Silt, Clay)	Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/, accessed on 16 April 2022)	2020 (China Mainland)
Population data	Raster (1 km)	Population density	Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/, accessed on 16 April 2022)	2020 (China Mainland)

3. Methods

The methodological framework of this research is divided into four parts (Figure 2). The first step is to construct the forest and grass ecospatial network. Land use types with typical ecosystem services are selected as ecological sources, and ecological corridors are the shortest paths for the source to pass through the least cumulative resistance surface. The second step is to calculate the three ecosystem services of water retention, soil conservation, and carbon storage in the study area based on the InVEST model [26,27]. Then, the third step calculates the degree, average path length, weight clustering coefficient, betweenness, PageRank, connectivity, node weight, unit weight, and weight distribution difference of the forest and grass ecospatial network. The last step is to analyze the relationship between the topological characteristics of the forest and grass ecospatial network and the three ecosystem services.

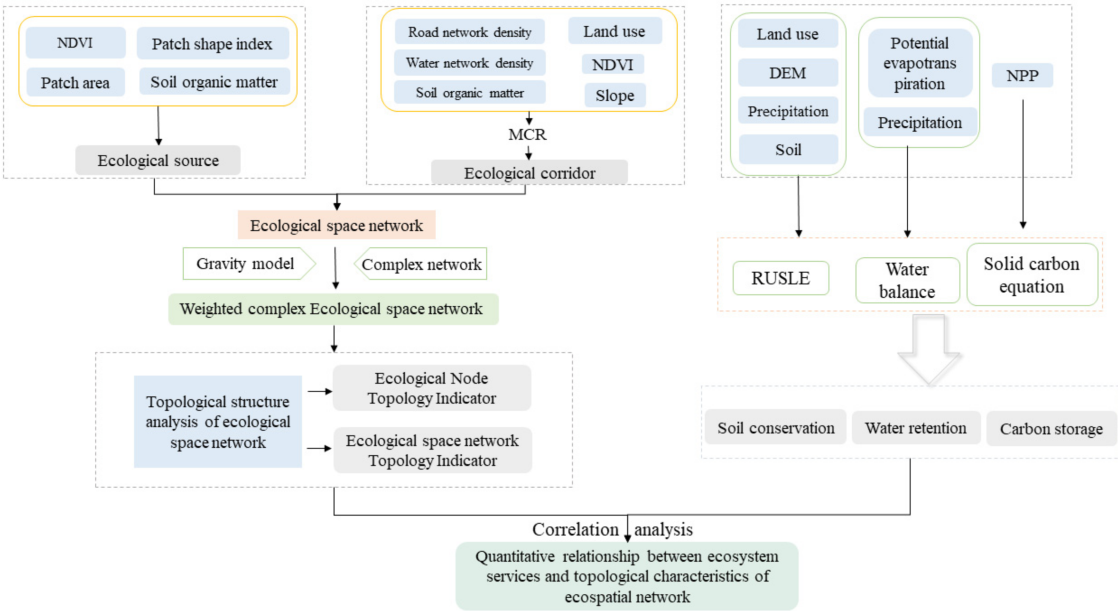

Figure 2. Schematic diagram of the study framework.

3.1. Empowering Ecospatial Network

3.1.1. Ecological Source

Ecological sources are ecological patches that provide key ecosystem services and play an important role in maintaining the continuity of ecological processes and preventing ecosystem degradation. In this paper, we analyze the topological relationship between ecosystem services and ecospatial networks; thus, three types of land use with typical ecosystem services, namely closed forest land, shrubbery, and high cover grass, are selected as ecological sources, and ecological sources are selected by four indicators: patch area, average NDVI, soil organic matter, and patch shape index [7,28,29].

The patch area is obtained by area statistics in ArcGIS software; the average NDVI is calculated by the zoning statistics tool in ArcGIS; soil organic matter is based on national soil data and presented spatially through raster data; the larger the patch shape index value, the higher the complexity of the landscape patches; finally, the entropy value method is applied to determine the patch area. The average NDVI, soil organic matter and patch shape index weights are determined through the entropy method to filter the ecological sources according to the importance level of the patches [28,30]. The calculation formula of the patch shape index is as follows.

$$Shape = \frac{0.25P}{\sqrt{A}} \tag{1}$$

where *Shape* is the patch shape index, *P* is the circumference of the patch, and *A* is the size of the patch

3.1.2. Ecological Resistance Surface Construction

Ecosystem services are the ecological processes of energy and information flow in the ecosystem. It is influenced by ecological resistance factors in the process of energy and information transfer, and the resistance surface constructed by ecological resistance factors reflects the trend and pattern of ecological flow in the ecosystem. Referring to relevant literature [31–33], six ecological resistance factors (Figure 3) are selected including land use, roughness, NDVI, road network density, water network density, and soil organic matter. Using the natural breakpoints in the ArcGIS reclassification tool, each factor resistance is classified into 5 levels, and then, the resistance factors are summed and calculated by the raster calculator to obtain the resistance coefficients. Considering that different resistance factors have essential contributions to the maintenance and development of the ecospatial network in the study area (Table 2), different resistance factors have the same weights [34]. Finally, the minimum cumulative resistance model is used to construct the resistance surface.

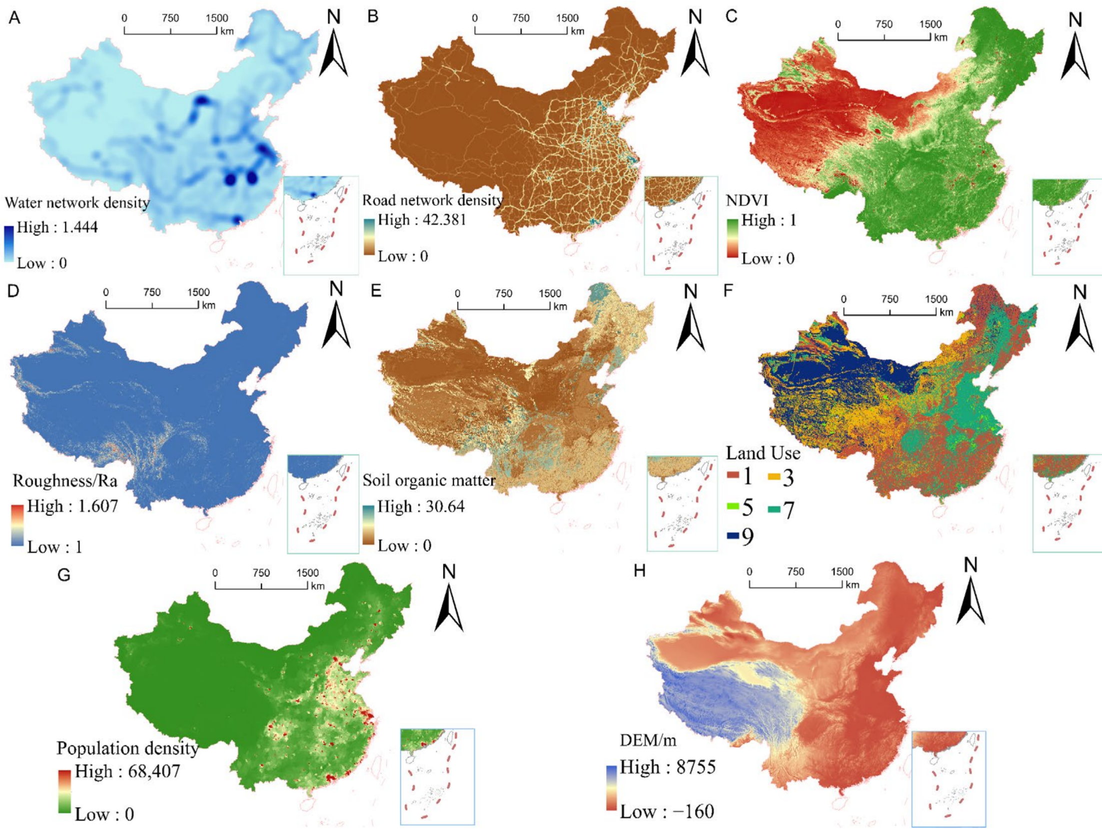

Figure 3. Results of factors for constructing ecospatial networks. (The meaning of land use 1, 3, 5, 7, 9 expressions are shown in Table 2).

Table 2. Ecological resistance factor evaluation system.

Factor	Value	Grade	Factor	Value	Grade
DEM/m	−160–718	1	Population density	0–266	1
	718–1717	3		266–2135	3
	1717–2999	5		2135–6941	5
	2999–4324	7		6941–18,422	7
	4324–8755	9		18,422–68,349	9
Land use	Closed forest land, Shrubbery, High cover grass	1	Road network density	0–0.82	1
	Open forest land, Other forest land, Medium cover grass, Low cover grass	3		0.82–2.15	3
	rivers and canals, Lakes, Reservoir ponds, Mudflats, Beach	5		2.15–6.36	5
	Water Field, Dryland, Urban land, Rural settlement, Other construction land	7		6.36–11.87	7
	Sandy, Saline soil, Marshland, Bare land, Bare rock texture	9		>11.87	9

Table 2. *Cont.*

Factor	Value	Grade	Factor	Value	Grade
Roughness/Ra	1–1.007	1	Water network density	0–0.07	1
	1.007–0.024	3		0.07–0.19	3
	1.024–1.054	5		0.19–0.44	5
	1.054–1.107	7		0.44–0.84	7
	1.107–1.607	9		0.84–1.44	9
NDVI	0–0.19	1	Soil organic matter	0–0.51	1
	0.19–0.42	3		0.51–1.42	3
	0.42–0.66	5		1.42–3.1	5
	0.66–0.85	7		3.1–6.82	7
	>0.85	9		>6.82	9

The MCR model, proposed by Knaapen in 1992 [35], is applied to the study of the process of species migration at first, and now has been widely used in the fields of ecological connectivity, species conservation, and landscape pattern analysis [36,37]. MCR can determine the shortest path between the starting ecological source and the target source, and describe the ecological resistance that needs to be overcome for the migration of ecological elements from one ecological sources to another. Using ArcGIS 10.4 cost path analysis tool, the minimum accumulated resistance to be overcome for the migration of elements between ecological sources is calculated, and the minimum cost path is identified as a potential ecological corridor [38,39]. MCR is calculated as.

$$T_{mcr} = f_{min} \sum_{j=n}^{i=m} D_{ij} \times R_i \tag{2}$$

where T_{mcr} represents the minimum cumulative resistance value; f_{min} denotes the minimum value of cumulative resistance per unit of land; D_{ij} denotes the spatial distance from the starting source i to the final target landscape unit j, and R_i denotes the resistance coefficient of the movement process of site unit i.

3.1.3. Ecological Corridor

Ecological corridors are generally defined as ecological environments with a ribbon or linear layout that can connect ecological units with a more isolated and dispersed spatial distribution [40]. The flow of energy in an ecosystem passing through an ecological corridor produces optimal ecological benefits. There are multiple paths for landscape ecological flows to reach other sources from a certain ecological source through ecological resistance surfaces, and ecological corridors are the optimal paths to be selected from these paths. In this paper, the ecological corridors between ecological sources are extracted based on the cost–path model by the ecospatial network builder (graphab-2.6.1) [41].

3.1.4. Gravity Model

The ecological function of each ecological sources and the cumulative resistance value of ecological corridors in the ecospatial network are different; thus, the ecospatial network belongs to the undirected weighted network. In this paper, the interaction strength between ecological sources was quantitatively evaluated based on the gravity model, so as to scientifically determine the relative importance of ecological corridors [8]. The weight of each ecological source was obtained by adding the weights of the corridors connected to the ecological source. The calculation formula is as follows.

$$S_a = \sum_{b=1}^{N} T_{ab} = \sum_{b=1}^{N} \frac{L_{max}^2 \times \ln(S_a)\ln(S_b)}{L_{ab}^2 \times G_a G_b} \tag{3}$$

where S_a is the weight of ecological source, N is the number of neighboring sources of ecological source a. b indicates the ecological sources connected to a, and T_{ab} indicates the corridor weights of two ecological sources connected, L_{max} denotes the maximum resistance value of the ecological corridor, S_a and S_b denote the area of patches, L_{ab} represents the resistance value between two ecological sources, G_a and G_b are the resistance values of two patches respectively.

The weights of ecological sources and ecological corridors are calculated by formulas (3), and the two together constitute an empowered ecospatial network, which is used as the data and theoretical basis for the study in this paper.

3.2. Ecosystem Services

3.2.1. Water Retention

Water retention is an estimation method based on water balance [42]. Mainly based on the Budyko curve and the average annual precipitation, the water production of the grid unit is obtained by subtracting the evapotranspiration from the precipitation, thereby obtaining the water production in the entire ecosystem. In the model calculation, the confluence process is simplified, and the interaction between surface water and groundwater is ignored, so as to obtain the spatial distribution of water supply in the study area [43]. The calculation formula is as follows.

$$Y_{xj} = P_x - AET_{xj} \tag{4}$$

where Y_{xj} represents the annual water production of land type j in raster cell x; AET_{xj} represents the annual actual evapotranspiration of land type j in raster cell x; P_x is the annual precipitation of raster cell x.

3.2.2. Soil Conservation

The soil conservation of vegetation is equal to the difference between the potential soil erosion and the actual erosion. In this paper, the revised Universal Soil Loss Equation (RUSLE) was used to assess soil holding capacity [44,45]. The calculation formula is as follows.

$$CA = PA - A = R \times K \times L \times S \times M \times (1 - C \times P) \tag{5}$$

where CA is soil conservation (t/(km^2·a)); PA is potential soil erosion (t/(km^2·a)); A is actual soil erosion (t/(km^2·a)); R is Rainfall erosivity factor; K is soil erodibility factor; L is slope length factor; S is slope factor; C is surface cover and management factor; P is soil and water conservation measure factor; M is correction factor.

3.2.3. Aboveground Carbon Storage

All carbon storage expressed in this paper is aboveground carbon storage. In an ecosystem, plants perform the process of photosynthesis, absorbing carbon dioxide and releasing oxygen [46]. Based on the photosynthesis formula and NPP calculations, 1 kg of carbon is equivalent to 2.22 kg of organic matter [47]. The chemical equation for photosynthesis in green plants:

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

Vegetation can fix 1.63 kg of CO_2 and release 1.19 kg of O_2 per 1.00 kg of organic matter produced, and 1 kg of CO_2 contains 0.27 kg of carbon [48]. Calculation of carbon storage in China in 2020 comes from vegetation NPP data. The calculation formula is as follows.

$$W_{CO_2} = NPP \times 2.2 \times 1.63 \tag{6}$$

$$W_C = W_{CO_2} \times 0.27 \tag{7}$$

where W_{CO_2} denotes the amount of CO_2 fixed per unit area of the ecosystem (g/m^2), and W_C denotes the corresponding amount of carbon sequestered per unit area of the ecosystem (g/m^2).

3.3. Forest and Grass Ecospatial Network Topology Index

Ecospatial network is an important concept in landscape ecology, which constructs the linkage between ecological processes and ecosystem services [39]. When ecological sources are abstracted as nodes and ecological corridors as edges, the structure of the forest and grass ecospatial network is abstracted as a complex network. The topological structure of the network can be used to express the intrinsic relationship between ecological sources and the connectivity of the entire forest and grass vegetation. The flow of materials, energy and species between ecological source in different ecological processes is not exactly in the same direction; thus, there is a situation that each patch in the network is both a source and a sink. In this study, based on complex network theory, degree, weighted clustering coefficient, node weight, unit weight, weight distribution difference, betweenness, and PageRank were selected to analyze the topology of the network (Table 3). In addition, the formulas for calculating these topological metrics are described in the Supplementary Materials.

Table 3. Description of the topological indicators.

Name of Indicator	Introduction to the Algorithm	Ecological Significance of the Indicator	Reference
Degree	Number of connected edges of the node in the network	Number of ecological corridors connected to ecological source	[39]
Weighted clustering coefficient	Ratio of the actual number of connected edges of a node to the maximum possible number of connected edges	Proportion of connectivity between ecological source	[49]
Node weight	Network node weights	Weighting of ecological source	[50]
Unit weight	The average weight of the edges connected by the network nodes	Average weight of corridors connected by ecological source	[50]
Weight distribution difference	Degree of aggregation and dispersion of the distribution of node-connected edge weights	Aggregation and dispersion of weight distribution of ecological corridors connected to ecological source	[50]
Betweenness	The importance of two nodes connected to each other	Importance of connectivity between ecological source	[49]
PageRank	Metrics for assessing the importance of network nodes	Degree of importance of ecological source	[39]

3.4. Correlation Analysis between Topological Indicators of Ecospatial Network and Ecosystem Services

The forest–grass ecosystem composed of ecological sources in the ecospatial network has three typical ecosystem services: water retention, soil conservation and carbon storage. The exchange and interaction of ecosystem services are carried out through the ecological corridors in the ecospatial network. Therefore, this paper analyzes the correlation characteristics between ecospatial network topological indicators and ecosystem services through the Pearson correlation coefficient [51]. The calculation formula is as follows.

$$R = \frac{\sum(x-\overline{x})(y-\overline{y})}{\sqrt{\sum(x-\overline{x})^2\sum(y-\overline{y})^2}} \tag{8}$$

where R is the correlation coefficient. When $|R| > R_{0.05}$, that is, $P < 0.05$, the null hypothesis is rejected, and the correlation result is significant. When $|R| > R_{0.01}$, that is, $P < 0.01$, the null hypothesis is rejected, and the correlation result is significant.

4. Results

4.1. Analysis of China's Ecospatial Network

4.1.1. Ecological Sources

In this paper, three types of land use with typical ecosystem services, closed forest land, shrubbery, and high cover grass were selected as ecological sources. A total of 8163 ecological patches were selected as sources, with a total area of 1.962 million km^2, and the proportions of closed forest land, shrubbery, and high cover grass were 71.7%, 20.3%, and 8%, respectively. (Figure 4) The closed forest land is mainly distributed in the Northeast Forest Belt and southern China. The shrubbery patches are scattered, mainly in southwestern China. High cover grass have the highest degree of fragmentation and are mainly distributed in the northern sand control belt, the eastern side of the Inner Mongolia Plateau, and central China. The ecological patches in Northwest China are severely fragmented, and the number is relatively rare, mainly due to the unique temperate continental climate in Northwest China, with a high temperature in summer, scarce precipitation, and severe cold and dry winter, resulting in the distribution of large areas of grassland, desert, Gobi, sandy land and bare land that make it difficult to form an ecological source.

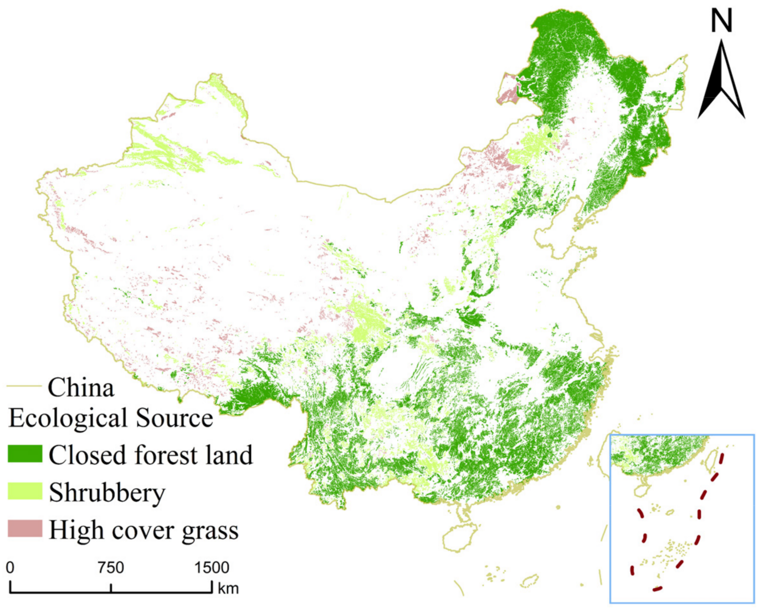

Figure 4. Ecological sources of the study area.

4.1.2. Ecological Resistance Surface

China's ecological resistance space has obvious differences, and the basic resistance value is between 1–72 (Figure 5B). Overall, Northeast China, Central China, and South China have lower resistance values, while Northwest and Southwest China have higher resistance values. The basic resistance value of the Northeast Forest Belt and South China Region is the lowest, mainly because the large area of arbor and shrub forests can provide good water retention, soil conservation, carbon storage, and strong ecosystem services. The North China Plain, the Northeast Plain and the Sichuan Basin are more suitable for planting crops due to their flat terrain and sufficient water resources. Therefore, farmland is widely distributed in these areas, and the ecological resistance value is in the middle. Due to the high altitude and low water network density in the vegetation coverage area of the Qinghai-Tibet Plateau, the regional ecological resistance value is relatively large. Due to the spread of bare desert land in Northwest China, the ecological resistance value is the highest, mainly because of the harsh ecological environment, mainly sandy land, scarce ecological patches and severe fragmentation to form a complete ecological corridor, which greatly hinders the ecosystem services between different sources.

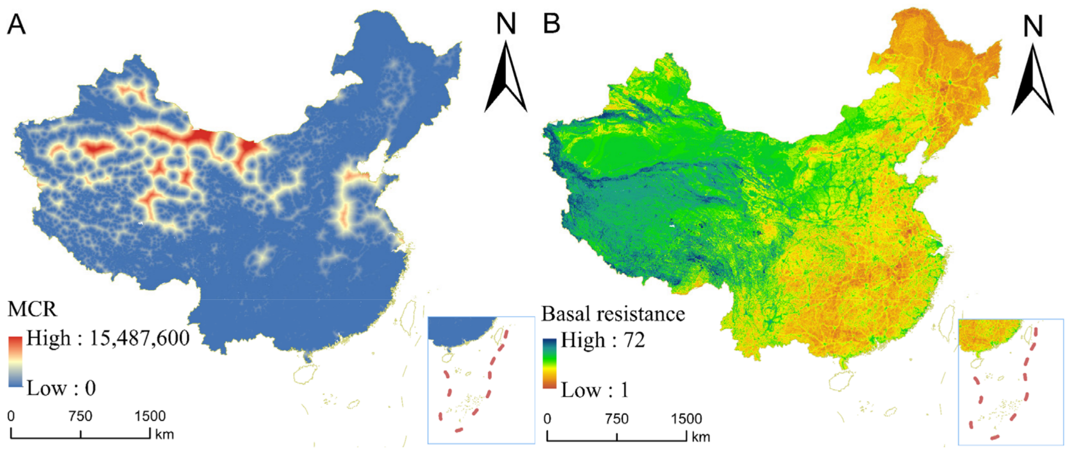

Figure 5. Minimum cumulative resistance surface (**A**), basal resistance (**B**) in the landscape spatial structure in China.

4.1.3. The Construction of Landscape Ecospatial Network

In this paper, we use Graphab software to extract ecospatial networks and construct a total of 13,264 ecological corridors (Figure 6). The ecological corridors in the northeast plain and the south of China are more densely distributed, indicating that ecosystems have a strong circulation in ecological processes of energy and material flows; The ecological environment in Northwest China is poor, and the ecological patches are severely fragmented, which makes it difficult to form a stable ecological flow, resulting in a sparse distribution of ecological corridors between different source; the North China plain has a large range of arable land and fewer ecological corridors; short ecological corridors were scattered in the Northeast Forest Belt and South China region, because the ecological sources were large and close to each other; thus, the ecological corridors were sparse and short.

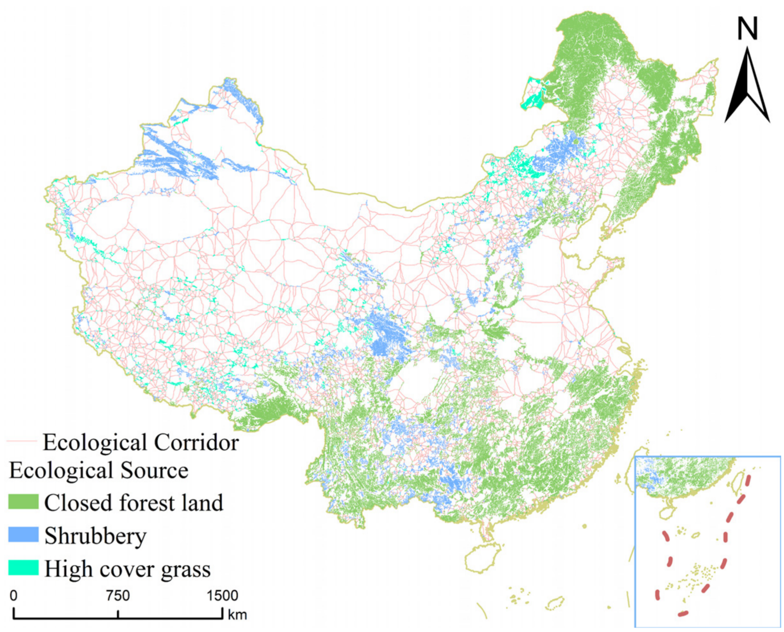

Figure 6. Ecospatial network of the Study Area.

4.2. Ecosystem Services

4.2.1. Water Retention

The distribution of water retention in the study area has obvious spatial variability, with an overall characteristic of high in the southeast and low in the northwest, decreasing from east to west, and forest ecosystems in areas with higher precipitation south of the Yangtze River play an important role in water retention (Figure 7C). In the range of 0–3145.31 mm/km^2 in 2020, the spatial distribution characteristics of water retention in China are consistent with the division of arid, semi-arid, humid, and semi-humid regions in China, indicating that the intensity of rainfall affects the spatial distribution of regional water retention. In South China, the water retention is greater than 1000 mm/km^2, with high vegetation coverage and sufficient annual average precipitation. It reduces the transpiration of the ground, reduces the loss of water in the soil, and the forest canopy and vegetation trap part of the precipitation, which has the effect of cutting down the soil erosion caused by excessive precipitation. Furthermore, sufficient regional precipitation will supply water to the small watershed. By regulating the regional water flow and the water cycle in two ways, the water holding capacity is enhanced, which has a positive impact on promoting ecological flow processes in the ecosystem and facilitates the generation of ecological corridors between different sources. Water retention in southwest and central China ranges from 500–1000 mm/km^2, and belongs to a subtropical humid climate zone with masson pine forests, fir forests, evergreen broad-leaved forests and local subalpine scrub meadows, etc. The forest ecosystem provides good regional water retention services; the Greater Khingan Mountains, Xiao Hinggan Mountains, and Changbai Mountains are located at high latitudes, and the vegetation is mainly cold temperate coniferous forests, but the regional precipitation is low and the vegetation evapotranspiration is large; thus, the water retention is in the middle level in China. The Inner Mongolia Plateau and Qinghai-Tibet Plateau have the lowest water retention (Figure 6). The regional vegetation composition is mainly grass ecosystems with low annual precipitation (below 400 mm). In addition, the soil undergoes long-term weathering, erosion by erosion and wind erosion, and the regional water retention decreases.

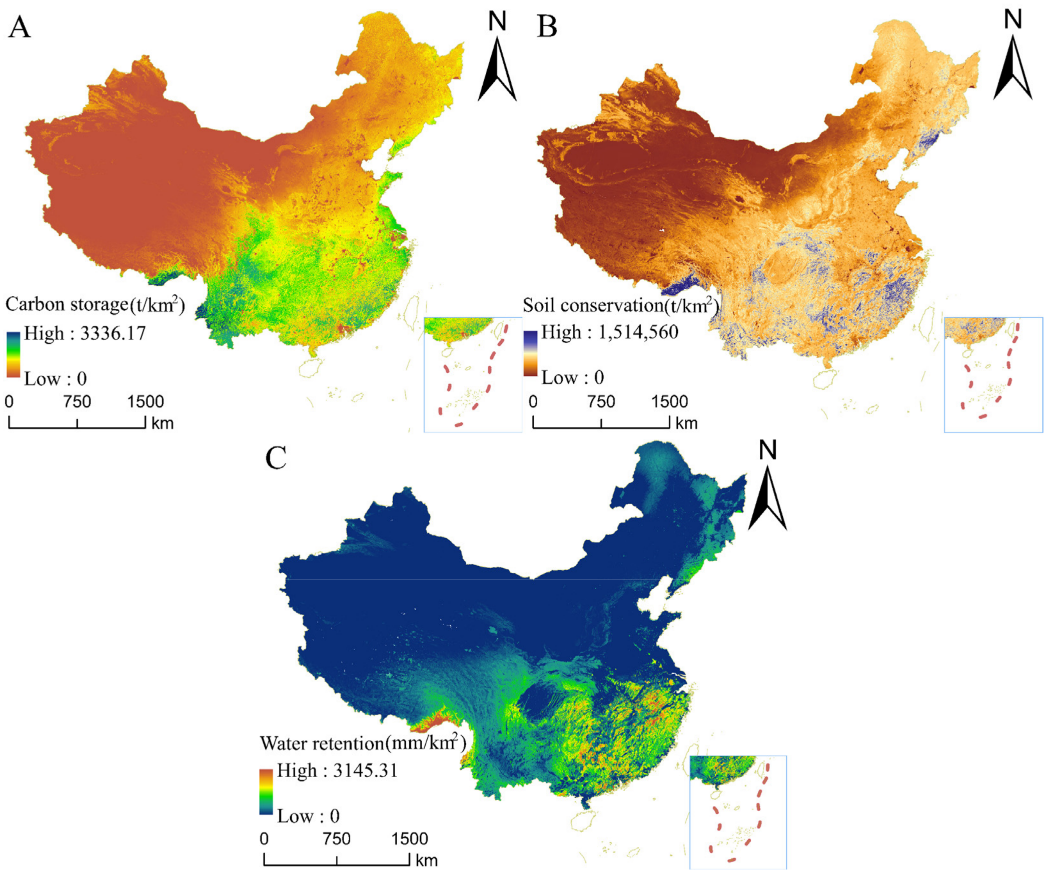

Figure 7. Carbon storage (**A**), soil conservation (**B**), and water retention (**C**) in the study area.

4.2.2. Soil Conservation

The spatial distribution pattern of soil conservation in the study area is relatively uniform, with soil conservation in central, eastern, southern, and partly southwestern China being greater than that in northeastern, northern, and northwestern China (Figure 7B). The soil conservation in the lower Yarlung-Zangbo River and the South China region is greater than 100,000 t/km^2; especially, the soil conservation in the lower Yarlung-Zangbo River is the largest. The terrain in this area is relatively low and flat, surface water is abundant, the warm and humid airflow from the Indian Ocean can travel and lift along the river valley; thus, the rainfall is also relatively large, and some coniferous and broad-leaved forests are also distributed in these areas. Trees will reduce soil erosion and stabilize the soil, and the terrain is flat and the potential soil loss in the region is low; thus, there are obvious spatial differences in soil retention between the lower Yarlung Tsangpo River and other regions in China. Soil conservation in the Northeast Forest Belt ranges from 10,000–100,000 t/km^2. The Northeast Forest Belt is distributed with coniferous and deciduous broad-leaved forests with good soil conservation function, but the potential soil loss is high due to the undulating terrain of the region. Moreover, the Northeast Forest Belt borders Inner Mongolia, and there is a certain amount of sandy grassland, which can cause different degrees of soil erosion. Thus, overall, it seems that the soil retention capacity of the northeastern forest belt is slightly lower than that of the arboreal forests in the lower Yarlung Tsangpo River. Soil conservation is extremely low in the northwest region of China. It is mainly due to the sparse vegetation and low rainfall in the western region, resulting in reduced water quantity in some watersheds, as well as desertification, degradation, and alkalinization of grasslands caused by overgrazing of grasslands, which lead to serious regional soil erosion and greatly affect soil conservation in the northwest region.

4.2.3. Aboveground Carbon Storage

The spatial distribution of carbon storage services and water retention in the study area is similar, with carbon storage in China ranging from 0–3336.17 t/km^2 in 2020 (Figure 7A). The strongest carbon storage services are found in the lower Yarlung Tsangpo River and the southern side of the Yunnan-Guizhou Plateau, reaching more than 2000 t/km^2. Other woodland-covered areas have the next strongest carbon storage capacity, with sufficient regional water sources and the distribution of large coniferous and broad-leaved forests, which have good carbon storage capacity; The amount of carbon storage in the northeastern forest belt, Central China and South China fluctuates above and below 1000 t/km^2; a large number of shrub forests are distributed in Northwest China, and the amount of carbon sequestered is around 500 t/km^2. Northwest China has the lowest carbon storage areas in China, mainly due to the low vegetation cover and severe desertification, and the fragile ecological environment. By calculating the average carbon storage of 1 km^2 in different ecological sources, (Figure 8), the carbon storage of a closed forest land ecological source is larger than that of shrubbery, and the carbon storage of shrubbery ecological sources is much larger than that of high cover grass, which indicates that there is a great difference in carbon storage service between different ecological sources.

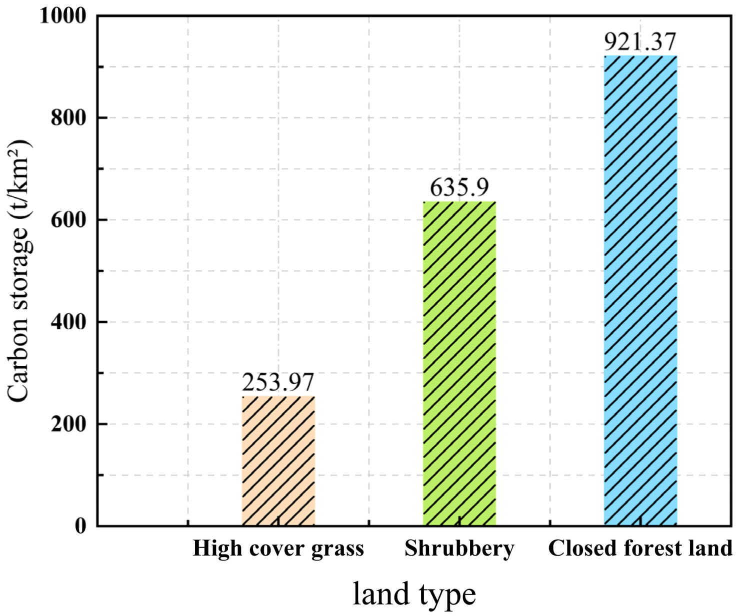

Figure 8. Average carbon storage in 1 km^2 of three ecological sources.

4.3. Analysis of Topological Structure of Ecospatial Network in China

Analysis of Ecological Source Topological Index Results

In the ecospatial network, the greater the degree value of the ecological sources, the greater the number of ecological sources connected to it. The spatial distribution pattern of degree is similar to that of different types of ecological source, the degree value of closed forest land is larger than that of shrubbery, and the degree value of shrubbery is larger than that of high cover grass. The spatial connectivity of the spatial network of forest ecosystems is greater than that of grassland ecosystems. It can be seen that the spatial distribution of the degree values of ecological sources has obvious spatial aggregation (Figure 9A), the degree values range from 1 to 123, and there are no isolated ecological sources in the overall ecospatial network. The degree values of 69–123 are mainly distributed in the northeastern forest belt and southern China, where coniferous and broad-leaved forests are mainly distributed, indicating that the ecological flow is more smoothly transmitted between forest ecosystems. The largest ecological source is located in the Wuyi Mountains, with a large area and a northeast–southwest orientation, as an "intermediary source" connecting the Nanling Mountains, the middle and lower reaches of the Yangtze River Plain, the Huangshan Mountains, and the Luoxiao Mountains. In the southwest, east and central China, there are closed forest land, shrubbery, and high cover grass with abundant rainfall and a good ecological environment, and the transmission of ecological flows between different ecological sources is more frequent. Ecological patches in the northwest region of China are scarce, and the fragmentation of patches is serious, and it is difficult for ecological flows between different ecological source to form ecological corridor; thus, the degree value of ecological source in the region is generally low.

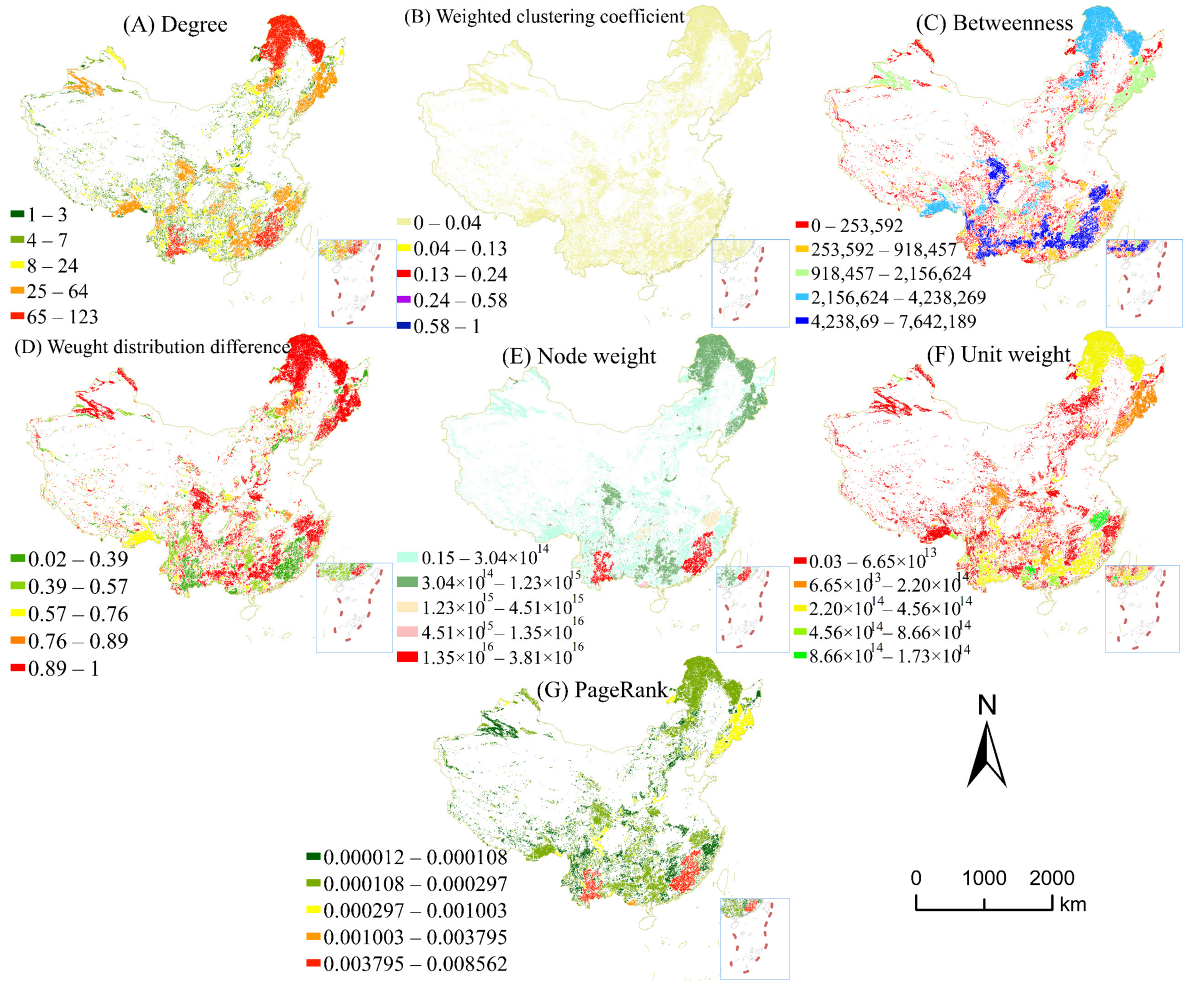

Figure 9. Ecospatial network topology index degree (**A**), weight clustering coefficient (**B**), betweenness (**C**), weight distribution difference (**D**), node weight (**E**), unit weight (**F**), PageRank (**G**).

The larger the weighted clustering coefficient, the more frequent the connection between ecological sources and neighboring ecological sources (Figure 9B). Among them, there are 3864 ecological sources with the weighted clustering coefficient of 0, which was mainly distributed in the northwest region of China, indicating that the sources in these regions do not have aggregation characteristics. Those with weighted clustering coefficients in the range of 0.6–1 are mainly distributed in the southern hills, the Yunnan-Guizhou plateau, and the Qinling-Daba Mountain area, which have strong clustering characteristics and strong connectivity between ecological sources and neighboring sources. The large differences in the clustering coefficients of ecological sources in different regions were analyzed, indicating that the spatial ecological network in China has strong heterogeneity.

PageRank can comprehensively describe the importance of nodes through the number and quality of connections between nodes and is an important indicator to measure the efficiency of energy flow and information transmission in ecospatial networks. The spatial distribution of PageRank has obvious spatial differences. The highest degree of importance of ecological source was found in South China and Southwest China regions (Figure 9G). Among them, more than 87% of the ecological sources have PageRank less than 0.0002, indicating that the PageRank of the overall ecospatial network is not strong.

The largest weight distribution difference is found in the Northeast Forest Belt, South China, and Xuefeng Mountains, indicating that some of the ecological corridors in these regions take on more transmission roles. It can be seen that there are differences in the transmission of ecological flows between different types of ecological source (Figure 9B), and when comparing the three types of land, the differences in the weights of shrubbery and closed forest land are not significant, and the differences in the weights of high cover grass ecological source are lower than the first two, indicating that the differences in the side weights of ecological corridors connected by high cover grass are small, and the energy output, supply, and transmission are more even among ecological corridors.

The unit weight expresses the average ecological energy flow that ecological sources can transmit to the ecological corridors connected with them (Figure 9F). The high value of unit weight is concentrated in the vicinity of Yunnan-Guizhou Plateau, Daba Mountain, and Wuyi Mountain Range. This indicates that the regional ecosystem service is stronger and can transmit more ecological flows to the neighboring source areas. In addition, comparing the range of unit weight and average unit weight of the three types of land, we found that the unit weight of high cover grass was smaller than those of shrubbery and closed forest land, indicating that closed forest land and shrubbery can transmit more ecological flows with the same degree of ecological corridor connection.

4.4. Correlation Analysis of Forest–Grass Ecospatial Network

Water retention services have ecological functions such as regulating climate and maintaining ecological water balance, and each type of ecological source has unique water retention services. Soil conservation has soil retention capabilities to control erosion and intercept sediment. As the main provider of carbon storage in terrestrial ecosystems, vegetation has a strong carbon sequestration capacity. The three different ecosystem services are mainly related to woodland and grassland; thus, this paper selects closed forest land, shrubbery and high cover grass as the ecological source. Since there are three types of ecological sources, namely woodland, shrub forest, and high-coverage grassland, the water retention, soil conservation, and carbon storage capabilities are different. Therefore, the relationship between the topological indicators of different types of ecological sources and the three are analyzed. SPSS software was used to calculate the correlation between ecospatial network topological indicators and three ecosystem services. The unit weight, node weight, degree, weighted clustering coefficient, weight distribution difference, PageRank, and betweenness are selected in this paper (Figure 10). The weighted clustering coefficient has no spatial correlation, but the degree, point weight, unit weight, PageRank, betweenness, and the three ecosystem services are all the same in all land types. It showed a significant positive correlation feature. The correlation analysis of water retention, soil conservation, and carbon storage found that the three have extremely significant positive correlation characteristics, and the three ecosystems have obvious synergy. The soil conservation and carbon storage corresponding to the high-value areas of water retention are also high-value areas. Therefore, in the following analysis, water retention, soil conservation, and carbon storage are collectively referred to as ecosystem services.

The larger the degree value of the ecological sources, the stronger the ability of the source to interact with other ecological sources, and more ecological flows will enter or flow through the source, making it have stronger ecosystem services. In the comparison analysis (Figures 7A and 8), it was found that the degree values of Northeast Forest Belt, South China and Southwest China were the largest, and the corresponding three ecosystem services were the strongest, and according to the correlation characteristics of the three land types, the correlation coefficient of closed forest land is close to that of shrubbery and much higher than that of high cover grass, indicating that the relationship between ecological energy transfer and ecosystem services is better reflected in forested land than grassland. (Figure 7). It can be seen that forested land with a large number of ecological corridor connections is more likely to have extremely strong ecosystem services at the same time.

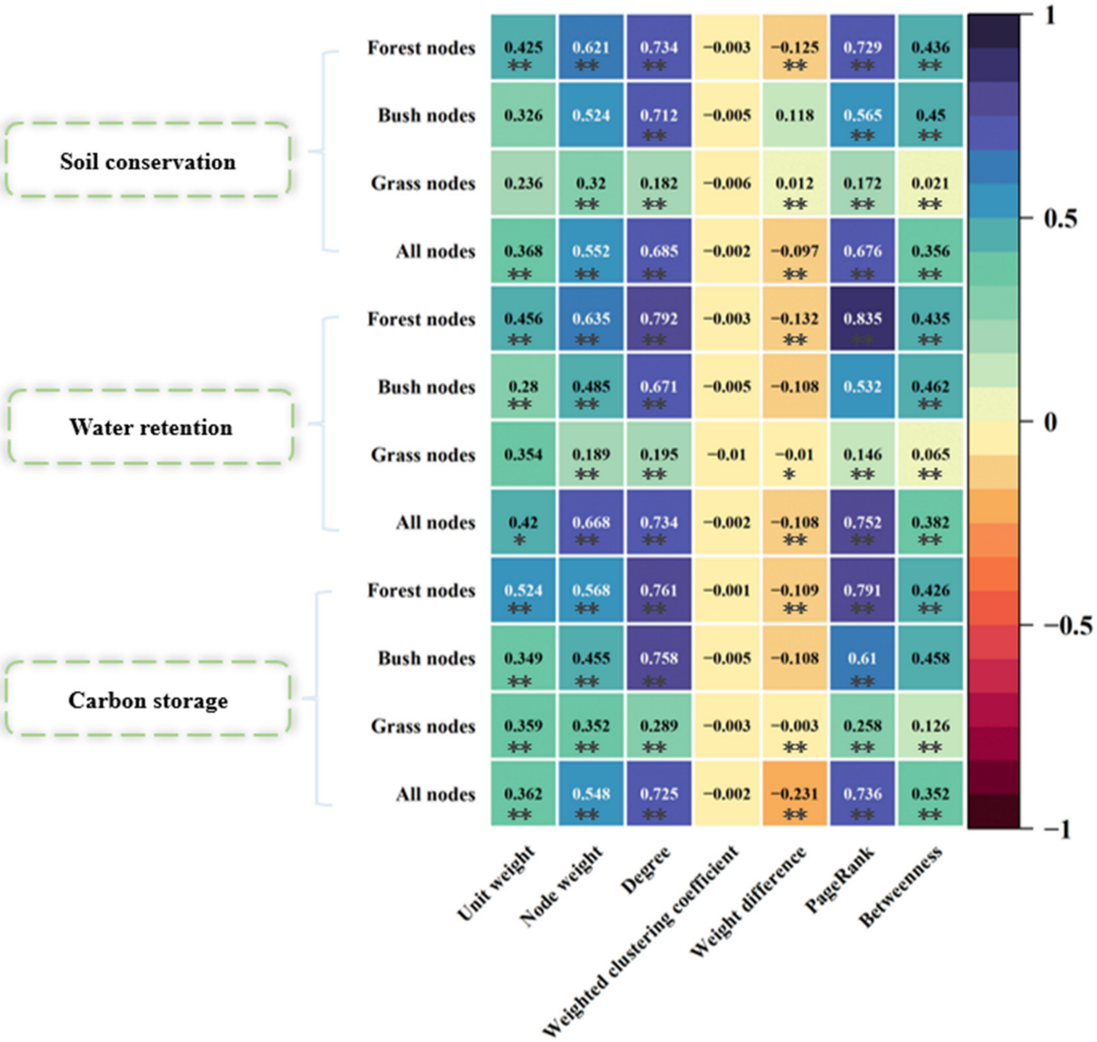

Figure 10. Correlation between topological indicators of eco-space network and ecosystem services. The asterisks donate statistical significance: * $p < 0.05$, ** $p < 0.01$.

The node weight expresses the ecological flow that ecological sources can transmit through ecological corridors, while the unit weight expresses the average side weight of ecological corridors connected to specific ecological sources, and the unit weight is the largest in the Northeast Forest Belt, South China and Southwest China, indicating that the stronger the ecological corridor connections in these regions, the more ecological flow can be transmitted to other ecological sources, which can make the ecosystem service to play an important radiative effect. However, the node weight of the Northeast Forest Belt regions is low, because the northeastern part of the Greater Khingan Mountains is adjacent to Inner Mongolia, and the ecological environment of this region is poor and does not use the ecological flow transmission. Furthermore, the middle of the northeastern forest belt is the northeastern plain is mainly planted crops, which also greatly reduces the northeastern forest belt ecological flow energy transmission. The region has a large area of broad-leaved forests and coniferous trees, but the transmission between its ecological flows is severely impeded.

PageRank describes the degree of importance of an ecological source in relation to other neighboring ecological sources. It can be seen that PageRank has obvious spatial variability. The PageRank of the Northeast Forest Belt, South China and Southwest China is the highest. It indicates that this region is an important area for maintaining ecological energy flow and material circulation in southern China, and there will be many ecological energy flows to or through this ecological source area. The northwest region has the lowest PageRank value. The source areas are severely fragmented and have few ecological corridors, and the overall ecological environment is relatively poor. The larger the source site's medium value, the more important it is as a "stepping stone" between the two source communities, and as an intermediate contact between them. Therefore, the ecological source of this large value plays a vital role in the connectivity of the whole ecological network and should be protected in the future ecological construction. The Greater Khingan Mountains, Xiao Hinggan Mountains, Northeast Forest Belt, Northwest China, and South China are all particularly important sources connecting other ecological sources, and the sources with large meso values have obvious spatial aggregation, with larger meso values in northeast, east, south, and east of southwest regions, and smaller meso values in northwest, north, central, and west of southwest regions. This indicates that the ecosystem services have obvious spatial variability.

5. Discussion

In present paper, land cover types with typical ecosystem services are selected as ecological sources, including closed forest land, shrubbery, and high cover grass, which are three land use types that can more realistically reflect the transmission of ecosystem services in the ecospatial network [52]. In natural ecological landscapes, the weights vary among different ecological sources, and the ecological flows of ecosystem service transmission are difficult to assess in natural spatial networks; thus, it is necessary to establish a method to quantify the ecospatial network. In the present research, based on the complex network theory, we constructed an ecospatial network to simulate a real ecological landscape [29] combined with a gravity model. The topological indicator system of the complex network theory is used to abstractly describe the ecological energy flow process of ecosystem services, explore the relationship between different ecospatial network topological indicators and three ecosystem services (water retention, soil conservation and carbon storage), and deeply investigate the correlation between different topological indicators and three ecosystem services.

The density of the forest and grass ecospatial network in China has obvious spatial heterogeneity. The network density in the southeast region of China is higher than that in the northwest region, and the density of the network from the east to the west shows a decreasing characteristic. The ecological sources in Northwest China are severely fragmented, and the ecological flows within sources are insufficient to support the formation of complete corridors between two sources. The Northeast Plain and Inner Mongolia Plateau create a great obstacle for the transmission of ecological energy in the Northeast Forest Belt. Therefore, changing the spatial structure of the landscape from a macro perspective based on national engineering construction is considered to improve ecosystem services in China [53]. In this paper, we explore the intrinsic relationship between topological indicators of ecospatial networks and ecosystem services and propose optimization strategies of ecospatial networks, which have great research significance for enhancing the ecosystem services in China. In the present study, the correlation analysis between topological indicators and ecosystem services was conducted separately for three different vegetation types. It was found that forest land has the strongest correlation with ecosystem service, while grassland had the weakest, which is congruent with the studies of [54,55], indicating that forest ecosystem service was greater than grassland ecosystem service. The forest ecosystem service is stronger in the Greater Khingan Mountains, Lesser Khingan Mountains and Changbai Mountain areas, and the transfer of ecological flow between the intricate patches of ecological corridors within the forest is frequent. However, their PageRank values are low, indicating that the ecosystem service of the Northeast Forest Belt only has a weak ecological flow radiation effect on the surrounding Northeast Plain and Inner Mongolia Plateau. A study analyzed the ecological degradation mechanisms in the western part of the Northeast Plain over the last hundred years [56]. It was found that the ecological environment in the western part of the Northeast Plain has been increasingly degraded in the last hundred years, and the desertification landscape has become increasingly significant, with the original horqin grasslands no longer existing and the sanding of the Songnen meadow plain forming new sandy areas in the core area. This is mainly due to the gradual decline of ecosystem services in the western Northeast Plain caused by human overcultivation and overgrazing. Therefore, the sloping and sandy arable land with serious soil erosion and low and unstable yield can be considered to be restored to grassland to increase the ecological source land. Furthermore, overgrazing can be managed through national policies by implementing seasonal fallow lands to restore grassland vegetation during the spring pasture re-greening period and autumn pasture fruiting period, and implementing enclosures and grazing bans in ecologically fragile areas and areas with severe grassland degradation to improve the Northeast Plain ecosystem services. The Inner Mongolia Plateau in the western part of the Greater Khingan Mountains is characterized by severe land sanding and soil erosion, a general trend of grassland degradation and low total forest resources, and an extremely fragile ecological environment [57,58]. According to the local ecological protection and restoration project, we can consider the scientific creation of wind and sand forest by adopting measures such as fly-sowing afforestation, artificial grass planting, and mountain forestry and grass cultivation. In addition, for the rehabilitation of abandoned mines in Inner Mongolia plateau, the ecological environment in and around the mines is restored. The northwest region of China has low vegetation cover, mostly bare rock and gravel, desert and other areas with the lowest ecosystem service function. Moreover, the degree, meso, point power and PageRank values of ecological sources are low, indicating that the ecological energy contained in ecological source sites and the transmission of energy flow between ecological corridors in the northwest region are the worst in the whole eco-spatial network, which is also similar to the study of [59], where the ecological environment in regions with low topological indicators is poor and unfavorable for the transmission of ecological energy. The topography of the northwest region of China is characterized by undulating mountains, Gobi and desert, exposed bedrock and sparse vegetation in the vast majority of the area, and its fragile ecological environment [60]. In recent years, the rapid increase in population, overcultivation and grazing are leading to land desertification and desertification, which aggravate the deterioration of the ecological environment in the northwest region of China [61]. Therefore, combining the development and utilization of natural energy according to the local ecological environment and guiding people to use solar energy and wind energy for living and heating will greatly reduce the destruction of vegetation resources. It is supposed to strictly prohibit reclamation and limit the expansion of arable land to reduce soil erosion and soil fertility decline [62]. It can effectively prevent soil erosion, wind and sand control, and the increase in vegetation cover also facilitates the transmission of ecological flows between ecological sources, forming a virtuous cycle, which in turn enhances the ecosystem service in the northwest region of China.

This paper optimizes the ecospatial network based on the relationship between forest and grass ecospatial network topology and ecosystem services, which is innovative compared to previous studies that optimize ecospatial networks through landscape connectivity, ecological risk identification, and ecological suitability [22,63,64]. However, the study also has some limitations. One is that this paper determines the weights of each corridor based on the gravity model. This method of determining the weights takes into account the radiative capacity of ecological energy in the source and the ecological resistance in the process of propagation, which is reasonable to some extent. However, it is another more convincing way to assign weights by determining the amount of material, energy and species migration among ecological source through field survey and measurement, and then determining the corridor weights. However, current survey and measurement means are difficult to monitor the exchange of various materials and energy among ecological sources, which lead to errors in the assignment network. Therefore, research and development of a new survey and monitoring methods to improve the reasonableness of ecospatial network weights can be the goal of future research. Second, the scope of the study area is large, and China possesses major ecosystem services in different ecological subdivisions. For example, the northeast Greater Khingan Mountains and Changbai Mountains are dominated by water retention ecosystem services. In addition, the Inner Mongolia Plateau is dominated by wind and sand-fixing ecosystems. Therefore, the material flow, ecological flow, and information flow of major ecosystem services in small-scale regions can be studied, and the change pattern of eco-spatial network structure can be explored in depth, effectively targeting a certain ecosystem service to implement anthropogenic intervention to improve and enhance its ecosystem service.

6. Conclusions

In this paper, mainland China was selected as the study area. Based on complex network theory, the relationship between the topology of forest and grass ecospatial networks and ecosystem services was analyzed to obtain topological indicators with high relevance. Based on the ecological significance of the topological indicators, the forest and grass ecospatial network is optimized to improve the ecosystem services. This methodological framework provides a new way of thinking for the optimization of ecospatial networks. The main conclusions of this study are as follows.

(1) Ecosystem services (water retention, soil conservation, carbon storage) in China have obvious spatial heterogeneity (Figure 8), with ecosystem services being greater in southeast China than in Northwest China, and closed forest land ecosystem services being greater than shrubbery, while shrubbery ecosystem services are greater than those of high cover grass.

(2) The distribution of forest–grass ecological network topology indicators has obvious spatial clustering locally, but the overall forest and grass ecospatial network topology indicators show obvious spatial discrete characteristics.

(3) This paper has certain spatial limitations by using mainland China as the study area. Therefore, it is necessary to consider whether the methodological framework is universal for other regions, such as tropical, northern boreal and southern boreal regions, which is worth further study in the next step. In addition, in the correlation analysis chapter, seven topological indicators were found to have significant correlation only with degree and PageRank, indicating that ecosystem services of forest and grass ecological source sites have strong correlation with certain topologies. However, most of the topological indicators have low or almost zero correlation, which may be due to the large scale of the study area, resulting in low correlation of most topological indicators. Furthermore, most of the topological indicators selected in this paper have low correlation with the three ecosystem services. Therefore, it is necessary to analyze the correlations of different topological indicators with ecosystem services for small-scale ecological restoration areas (desert–oasis areas, typical mining areas, arid zone cities, etc.) to verify whether the strength of correlations is related to scale. In the future, precise protection of vulnerable source sites in the ecological–spatial network can be implemented based on the topology of ecological source sites. This will be the next direction that the authors need to study in depth.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs14194700/s1. References [65–67] are cited in the supplementary materials.

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