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Study on ecological function zoning of Gansu Province from the perspective of ecosystem service flow environment and culture coupling

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Abstract

Based on the environmental-cultural coupling perspective of ecosystem service flow, this study explored the flow, distribution and interaction of ecosystem services in different regions in Gansu Province, in order to provide scientific basis for ecological protection and resource management in the province. In this paper, InVEST model, MaxEnt model and coupling coordination degree model are adopted. Based on the quantitative assessment of the supply and demand of ecosystem services, the hot spot analysis and the measurement method of ecosystem service flow based on circuit theory are combined. Linkage Mapper was used to construct ecological resistance surfaces, simulate ecological processes, identify ecological corridors, and analyze the spatial distribution and flow patterns of service flows. The results show that there are significant regional differences in the supply of ecosystem services in Gansu Province, and there are contradictions between cultural services and ecological services in regional coordination. There is a large spatial difference in the coupling coordination degree of environment-cultural services, that is, there are four main types of ecosystem service supply-demand ratio: The spatial distribution characteristics of ecosystem service flows of high-supply-high demand, high-supply-low demand, low-supply-high demand, and low-supply-low demand indicate that environmental service flows and cultural service flows present different flow paths and connectivity in Gansu Province. Based on the above analysis results, this paper divides the ecological function zone of Gansu Province into ecological culture protection zone, ecological culture maintenance zone and ecological culture development zone, which is closely combined with the territorial spatial planning of Gansu Province and adopts regional policies to ensure the ecological security and sustainable development of Gansu Province.

1. Introduction

With the deepening of the concept of ecological civilization development, people's concept of well-being for a better life is also quietly changing. The pursuit of a better life has gone beyond basic material satisfaction (Costanza, et al.,2017) and turned to the desire for healthy soil, fresh air, clean water, beautiful environment, pleasant climate and cultural beauty. The integration of culture and tourism is becoming a new engine of economic growth (Irfan, et al.,2023). This development trend has put forward new challenges to the regional ecosystem, and the coexistence of culture and ecology has become the core competitiveness of future regional development. However, current studies on ecosystem services (ES) are somewhat inadequate in terms of spatio-temporal changes (Wang, et al.,2022), interrelationships (Liu, et al.,2024) and functional zoning (Zeng, et al.,2023). In particular, the dynamic change of ES (Xie, et al.,2017) and the tradeoff relationship (Vallet, et al.,2018) have not received sufficient attention. Therefore, with the deepening of research on ES and the improvement of understanding of the complexity of ES, the concept of ecosystem services flow (ESF) has gradually evolved (Wang, et al.,2022), emphasizing the flow and distribution of ES in different regions (Wang, et al.,2022). And the interaction between services (Bayala, et al.,2014). The study of ESF helps to reveal the tradeoff and synergistic relationship between services (Li, et al.,2024) and provides scientific basis for formulating reasonable ecological protection and resource management strategies (Bruck, et al.,2022). The combination of ESF and ecological function zoning can more effectively guide the optimal layout of territorial space (Chen, et al.,2022). By identifying key ecological functional areas, clarifying the dominant service types of each region (Ding, et al.,2023), and analyzing the dynamic changes of service flow (Wu, et al.,2023), the reasonable allocation and efficient utilization of ES can be promoted (Li, et al.,2021). Furthermore, this combined strategy aids in striking a harmonious equilibrium between the conservation of ecosystems and the advancement of economic prosperity, which in turn contributes to the realization of the Sustainable Development Goals.

At present, the research on ecological functional zoning can be summarized as follows: 1) Ecological function zoning based on different research methods, such as the index system construction based on remote sensing cloud computing and geographic information spatial analysis technology (Liao,2022), Self-organizing feature mapping neural network (SOFM) (Liao,2022) and Random Forest (RF) algorithm were used for unsupervised partitioning (Dahan, et al.,2024), and combined with analytic Hierarchy Process (AHP) to determine subjective weights for comprehensive weighted analysis. PLUS model (Zhang, et al.,2023) and Markov model are used to simulate land use. 2) Ecological function zoning based on different research scales, such as province (Lu, et al.,2023), city (Yang, et al.,2022), district (county) level (Yang, et al.,2022), etc. 3) Ecological function zoning based on different unit types, such as ES function evaluation (Wang, et al.,2017), ecological sensitivity evaluation (Kong, et al.,2024) and regional economic development evaluation (An, et al.,2022). Existing studies have effectively promoted the transformation of ESF studies from theory to practice (Vari, et al.,2024), but there are still the following deficiencies: First, existing studies on ESF mainly focus on supply services and regulation services (Campbell, et al.,2020), with little reference to support services (nutrient cycling, etc.) and cultural services (entertainment and scenic spots, etc.) (Campbell, et al.,2020). Make the conflict between ecological and cultural services obvious in regional coordination (Meng, et al.,2023); Second, current studies mainly focus on the assessment of cities and counties (Zhao, et al.,2023) and small watershed scales (Ding, et al.,2024), but rarely involve the national and provincial scales (Pittock, et al.,2012). In addition, the research area is concentrated in the coastal developed areas (Chen, et al.,2023), and less attention is paid to the northwest area, which is relatively fragile in ecology and lagging in economic development level (Li, et al.,2023).

Gansu Province is located in the northwest of China and serves as an important passage connecting the Central Plains and the Western Regions. It possesses abundant natural resources and unique ecosystems. However, the ecosystem of Gansu is facing severe challenges, including water scarcity, land degradation, and a decline in biodiversity. Additionally, there is a significant imbalance between the supply and demand of ES in Gansu Province, particularly in terms of cultural ES, such as the conflict between the protection of historical sites and economic development. Therefore, the main contributions of this study are summarized as follows:

1. Comprehensive Assessment of ES Supply and Demand: This study not only focuses on the supply and demand of ES but also reveals the differences in supply and demand across different regions of Gansu Province through a comprehensive analysis of their spatial distribution characteristics and dynamic changes. By selecting a variety of ES indicators that cover both environmental and cultural services, this study provides a new perspective for understanding their complex interactions.

2. Robust Model Evaluation through Multiple Assessment Methods: The study integrates various methods, including the InVEST model, MaxEnt model, and coupling coordination degree model, to systematically quantify the supply and demand of ES. By comparing the results of different models, the accuracy and reliability of the assessment are enhanced, overcoming the limitations that may exist with a single method. This provides a more solid basis for the scientific management of ES.

3. Comprehensive Risk Classification through Cluster Analysis and Spatiotemporal Visualization: The study employs cluster analysis to scientifically classify ES in Gansu Province, based on the spatial distribution and flow patterns of ESF. Additionally, through visualization, it intuitively displays the dynamic changes and spatial distribution characteristics of ESF., providing a direct reference for ecological functional zoning and resource management.

2. Research methods and data sources

2.1. Overview of the study area

Situated in the northwest region of China, Gansu Province (32°11 '-42 °57' N, 92°13 '-108 °46' E) holds significant geographic importance within the country's western area. Gansu boasts a total of 14 prefecture-level administrative entities, comprising 12 cities at the prefecture level and 2 autonomous prefectures. There are 86 counties in the province. The land area of Gansu Province is about 425,800 square kilometers, the terrain slopes from southwest to northeast, and the landform types are diverse, including mountain, plateau, plains, desert and other landforms (Figure 1). In terms of climate, Gansu belongs to the temperate continental climate, the annual precipitation gradually decreases from southeast to northwest, the southeast has more precipitation, while the northwest is dry and less rain.

Gansu Province not only has diverse landforms and unique climate, but also carries profound cultural resources. It is the cradle of the Yellow River civilization, the thrust of the Silk Road, the melting pot of multi-ethnic cultures, the witness of the red history, and the meeting point of religious cultures. From the thousand-year-old murals of the Mogao Grottos in Dunhuang to the magnificent Great Wall at Jiayuguan, from the Danxia landform in Zhangye to the Tibetan customs in Gannan, Gansu's cultural landscape is a colorful tapestry of history and modernity. The abundance of cultural resources plays a crucial role in boosting cultural tourism in Gansu and preserving the rich traditional culture of China. Gansu province is currently under ecological stress as it grapples with balancing economic growth and environmental preservation. The conflict between economic progress and protecting the environment is particularly evident in ecologically delicate regions, where economic advancement relies heavily on exploiting resources, leading to a decrease in ES supply.

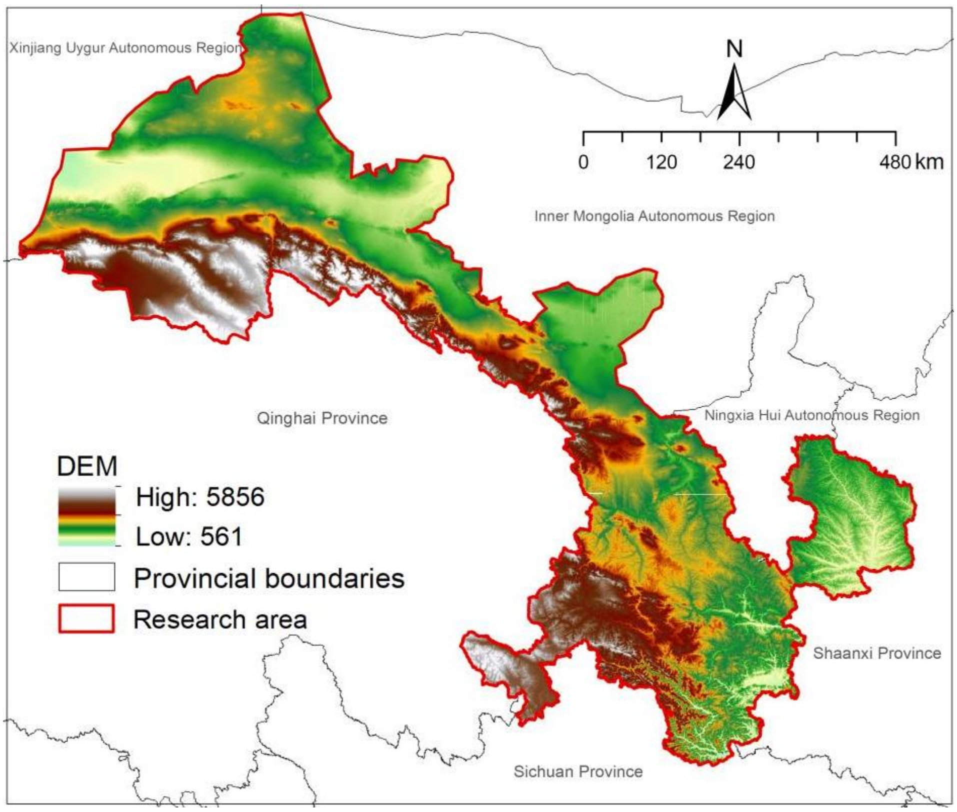

Figure 1. Location map of the study area

2.2. Research methods

2.2.1. Estimation of ES supply and demand

The study developed a comprehensive index system for ES supply by choosing four indicators for environmental services (water production, soil conservation, carbon sequestration, habitat quality) and four indicators for cultural services (historical heritage, local culture, recreational activities, scenic beauty) (Table 1).Currently, the measurement methods for ES supply include the emergy method (Li et al., 2023), value evaluation method (Zhang et al., 2023), and quality evaluation method. The emergy method converts services into energy units using solar value conversion rate and conversion function. However, not all ES have clear emergy conversion rates which result in uncertainties in analysis results at small regional scales. The value evaluation method monetizes the service value through benefit transfer or function value approaches. Nevertheless, it is subjective and may not fully reflect the real value of ES. On the other hand, quality assessment is based on ecological processes utilizing biophysical models such as InVEST model and CASA model to accurately depict the structure, function, and process of ecosystems providing scientific basis for decision-making. In this investigation, the spatial analysis of the ES provisioning pattern in Gansu Province was carried out by applying the InVEST model, MaxEnt model, and other relevant models. Ultimately, the assessment outcomes of diverse ES were standardized, weighted, and merged to acquire a holistic overview of Gansu Province's ecosystem service provisioning pattern.

Table 1. Assessment of ES supply

ES	Principle and method	Calculation process

Water production service	InVEST model Annual water yield module	Water Yield = P- (Q+E +S + GW) In the equation, Water Yield represents the quantitative result of water conservation function, P represents rainfall, Q represents surface runoff, E represents evapotranspiration, S represents the change of soil water content, and GW represents the groundwater recharge.
Soil conservation	InVEST model Sediment Delivery Ratio module	SD = RKLS -ULSE RKLS = R×K×LS USLE=R×K×LS×C×P In the formula, R represents the factor of rainfall erosivity; K represents the factor of soil erodibility; LS represents the factor of slope length; C corresponds to the factor of vegetation cover; and P indicates the factor of soil conservation measures.
Carbon sequestration service	InVEST model Carbon Storage and Sequestration module	$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead}$ Where: C_{above} is the amount of carbon stored on the ground; C_{below}x is the underground carbon storage; C_{soil}x is soil carbon storage; C_{dead}x is dead organic carbon storage.
Habitat quality	InVEST model Habitat Quality module	$\text{quality} = \sum(\text{sensitivity} * \text{threat distance}) / (1 + \text{protection})$ Where: quality represents the quality of the habitat, sensitivity represents the sensitivity of each habitat type to each threat, threat distance represents the distance between the grid cell and the threat, and protection represents the level of legal protection the cell receives.
History and culture	MaxEnt model	$H(P) = -\sum_{x \in X} P(x) \ln P(x)$ Where: H (P) represents the entropy of random variable X; P (x) is the probability that the random variable X is X; X is the set of all possible values of the random variable X; log represents the natural logarithm (the logarithm base e).
Regional culture	MaxEnt model	
Rest and recreation	MaxEnt model	
Aesthetic landscape	MaxEnt model	

ES demand refers to the degree of human society's dependence on and demand level of various services provided by ecosystem. It includes the need for basic ecological services such as clean water, clean air, food production, and climate regulation, as well as non-material services such as culture, education, and leisure. At present, the measurement methods of ES demand mainly include direct market value method, alternative cost method, conditional value assessment method (CVM), travel cost method (TCM), etc. (Sun, et al.,2022). Each of these methods has advantages and disadvantages: direct market value method is suitable for tradable services, but it is difficult to evaluate non-market value; The alternative cost method is applicable to the services that cannot be directly traded, but the determination of the alternative cost is subjective. CVM obtained payment intention through questionnaire survey, but it was affected by survey design and respondents' bias. TCM is based on the cost of travel and is suitable for leisure and tourism services, but it is difficult to quantify the demand for other services.

In recent years, researchers have proposed a method to construct ES demand index by combining land use intensity index with social and economic indicators such as population density and land per capita GDP. By quantifying the intensity of human activities' demand for ES, this method can reflect the dependence of different regions on ES. It combines the level of social and economic development and the characteristics of population distribution and provides a new perspective for regional ecological protection and sustainable development. The formula is as follows:

$$ESD = LDI \times \ln(POP + 1) \times \ln(GDP + 1) \quad (1)$$

$$LDI = 100 \times \left(\sum_{i=1}^{n} P_i \times Q_i \right) \quad (2)$$

Where: ESD serves the needs of the ecosystem; POP and GDP are population density and per capita GDP respectively. LDI is the comprehensive land use intensity index. P_i is the grade i land use intensity (i=1,2,3,4); Q_i is the percentage of area occupied by Class i land use type; n is the classification number of land use intensity.

2.2.2. Coordination degree of ecosystem environment-culture coupling

Coupling coordination degree is an important index to measure the relationship between ES and social and cultural development of human beings. There is a complex coupling relationship between ES and social and cultural development, which can be quantitatively evaluated by coupling coordination degree model. The level of coupling coordination reflects the matching degree between ES and social and cultural development, and the improvement of coupling coordination degree means the enhancement of synergistic effect between ES and social and cultural development (Yang, et al.,2022). The formula is as follows:

$$C = 2\sqrt{\frac{f(x) \times f(y)}{[f(x) + f(y)]^2}} \quad (3)$$

$$T = af(x) + bf(y) \quad (4)$$

$$D = \sqrt{C \times T} \quad (5)$$

Where: C is the coupling degree of the system; f (x) and f (y) are the comprehensive evaluation index values of environmental services and cultural services respectively, T is the comprehensive index of ES in Gansu Province, weight a and b are the undetermined coefficients of 0.5, D is the coupling coordination degree, the higher the value, the higher the degree of environmental and cultural coupling coordination.

2.2.3. Supply-demand ratio of ES

In order to explore the relationship between the supply and demand of ecosystem environment-cultural services in Gansu province, the ratio of ES supply and demand was used to represent the proportional relationship between the services provided by the ecosystem and the human society's demand for these services (Li, et al.,2016). The formula is as follows:

$$\mathrm{ESDR} = \frac{S - D}{(S_{max} + D_{max})/2} \tag{6}$$

Where, ESDR is the supply and demand ratio of ES, S is the supply amount of ES, D is the demand for ES, S_{max} is the maximum supply amount of ES, and D_{max} is the maximum demand for ES. When ESDR >0, supply is greater than demand. When ESDR =0, supply equals demand. When ESDR <0, supply is less than demand.

2.2.4. Hotspot analysis

Hotspot analysis is a spatial statistical method used to identify and quantify the concentration or aggregation phenomenon in geospatial data. In this study, the grid of 3000m×3000m is taken as the basic unit, and the Getis-Ord G_i^* cold hotspot tool of Arc GIS software is used to visualize the data (Hou, et al.,2018). The formula is as follows:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \overline{X} \sum_{j=1}^{n} w_{i,j}}{S\sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}} \tag{7}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - \left(\overline{X}\right)^2} \tag{8}$$

Where, G_i^* is the cold hot spot index, n is the number of patches: x_j is the attribute of patch j, $\overline{X}$ is the average value of all attributes, and w_{ij} is the spatial weight between elements i and j. According to the analysis results of the supply-demand ratio of ES, the supply-demand ratio of eight indicators of environment-cultural services was extracted with Hot Spot-99%Confidence and Hot Spot-95%Confidence to initially identify the supply source. Cold Spot-99%Confidence, Cold Spot-95%Confidence Initial identification of demand sources.

2.2.5. Estimation of ESF based on circuit theory

Circuit theory is an ecological tool that analogizes species migration and gene flow processes in an ecosystem to the flow of electrons in a circuit, simulating and analyzing ecological processes through the concepts of resistance and current. In this study, Linkage Mapper was used to quantify and visualize ESF (Shen, et al.,2022). Linkage Pathways is used to link ESF to physical current, simulate the random flow of ecological flow, calculate the current intensity between source areas, identify the ecological corridor in the landscape, and build a corridor connecting the supply area and demand area of ES. These corridors represent the potential flow paths of ES in space. Considering that different types of ESF may be affected by natural conditions or human activities during their flow, it is of great significance to add ecological resistance surface to the flow analysis of ESF, and the simulation results of the spatial distribution of ESF and their flow patterns under the action of multiple ecological factors will be more accurate. Seven factors, including land use type, elevation, slope, mountain shadow, vegetation coverage, distance from rivers, and distance from roads, were selected to construct the ecological resistance surface. The entropy method combined with the AHP was used to determine the subjective weights for a comprehensive weighted analysis to establish the weights of each resistance factor (Table 2). The combined subjective and objective weighting method initially uses the entropy method based on changes in the original data to determine the weights of each resistance factor. Subsequently, the AHP is employed in conjunction with expert opinions to adjust and optimize these weights(Xu, et al.,2024). This approach not only considers the objective changes in the data but also fully accounts for the actual importance of each resistance factor in the ESF, thereby providing a more scientific and reasonable basis for the construction of the ecological resistance surface. Finally, the comprehensive resistance surface is formed by overlaying these factors.

Table 2. Weight of resistance factors

Resistance factor	Description	weight
Height/(m)	As an important feature of natural topography, elevation has a significant impact on species migration and ecological processes. In resistance surfaces, areas with higher elevations are often assigned higher resistance values because they can be difficult to traverse, limiting the migration of species and the flow of ecological services.	0.1307
Slope/ (°)	The slope reflects the slope of the terrain and has an important effect on soil erosion and vertical distribution of species. In the resistance surface, steep slope areas will set higher resistance values because ecological processes and species migration in these areas are limited.	0.0997
Mountain shadow/(m)	Vegetation growth and species activity may be affected in mountain shadow area due to poor light conditions. In the resistance surface, these areas are assigned high resistance values to simulate the effects of insufficient light on ecological processes.	0.1142
Land use type	Different land use types have different effects on the supply and demand of ecological services. For example, construction land and farmland pose a large resistance to the flow of ecological services, so the resistance value of these areas will be relatively high in the resistance surface.	0.2546
Vegetation coverage	Vegetation coverage is an important indicator of ecosystem health and biodiversity. In the resistance surface, areas with high vegetation coverage have lower resistance values, because these areas are usually active in ecological processes, which are conducive to species migration and the flow of ecological services.	0.1497
By road distance/(m)	Areas with intensive human activities such as roads may interfere with ecological corridors. In the resistance surface, the resistance value of the area near the road is higher to reflect the negative impact of human activities on the ecological process.	0.1419
By water distance/(m)	Water bodies are an important part of ecosystems and are crucial for species migration and the flow of ecological services. In the resistance surface, the resistance value of the area away from the water body is higher, because the water body is a key factor in many ecological processes, and the distance from the water body may lead to the insufficient supply of ecological services.	0.1092

2.3. Sources of data

All the data in this study were selected in 2020, the spatial resolution of the data to be gridded was 30m ×30m, and the coordinate system was uniformly corrected to the WGS_1984_Albers projection coordinate system (Table 3).

Table 3. Data sources

Data	Source
Precipitation data and potential evapotranspiration data	National Tibetan Plateau Scientific Data Center (http://data.tpde.ac.cn)
Spatial distribution data of soil types	Geographic data platform, School of Urban and Environmental Sciences, Peking University(http://geodata.pku.edu.cn)
Elevation, normalized vegetation index, land use, administrative boundaries, road network, population and GDP grid data	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (https://www.resdc.cn/)
Amap POI (Point of Interest) data	Peking University open research data platform (https://doi.org/10.18170/DVN/WSXCNM)

3. Research results

3.1. Supply pattern of ES

Affected by topographic characteristics, the supply pattern of ES in Gansu Province showed obvious disequilibrium, with obvious differences between the east and the west (Figure 2). The western part of the region, represented by the Qilian Mountains, has high altitude and abundant precipitation. However, due to topographic reasons, the water production service supply function is limited and the regional soil conservation ability is relatively weak. However, the regional carbon sequestration service supply is relatively rich. In contrast, the lower topography and poor soil permeability of the eastern region, represented by the Loess Plateau and river valley landforms, lead to relatively low water production service supply capacity, and soil conservation service supply is also facing great challenges. However, the eastern region, with its numerous historical sites, cultural landscapes and natural landscapes, is prominent in the supply of cultural services.

In terms of environmental services, the high-altitude plateau area is the main supply area of water production services, while the low-altitude valley and Loess Plateau area face the problem of insufficient supply of water production services. In the soil conservation supply pattern, for example, in the middle and lower reaches of the Yellow River, the soil conservation service supply is relatively low because of the low terrain, poor soil permeability and less regional precipitation. For example, the forest areas of the Qilian Mountains and the Loess Plateau have high carbon sequestration capacity, while some nature reserves and ecologically sensitive areas, such as the Qilian Mountains National Park, provide good habitat quality. In terms of cultural services, Gansu Province has rich historical and cultural heritage, such as Dunhuang Mogao Grottoes and Maijishan Grottoes, which have made significant contributions to the supply of historical and cultural services, while some ethnic minority inhabited areas, such as Gannan Tibetan Autonomous Prefecture, have unique regional culture and folk customs, which have an important impact on the supply of regional cultural services. In terms of recreation, natural landscape and cultural attractions such as Zhangye Danxia landform and Tianshui Fuxi Temple provide tourists with abundant recreation resources; Qilian Snow Mountain and Yellow River Valley, these natural beauty and cultural landscape, provide people with aesthetic enjoyment.

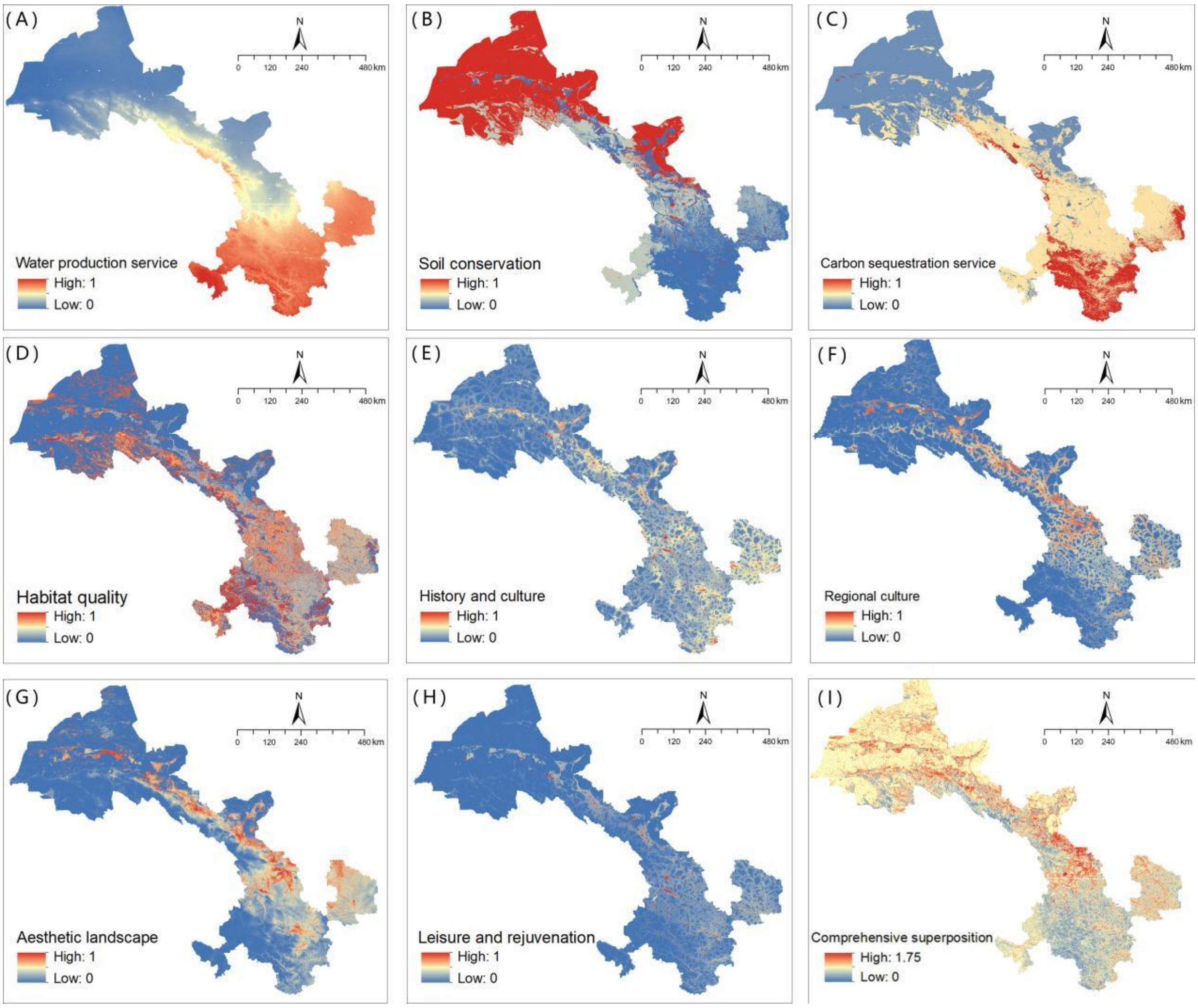

Figure 2. Supply pattern of ES in Gansu Province

3.2. ES demand pattern

The distribution of ES demand pattern in Gansu Province is affected by GDP per capita, population density, land use intensity and other factors. In Gansu Province, the regions with higher per capita GDP are mainly concentrated in Lanzhou and its surrounding areas, which are more advanced in economic development, with higher population density and urbanization level, and have more urgent demand for ES. The areas with high population density are mainly concentrated in large cities such as Lanzhou and Tianshui and their surrounding areas. Residents in these areas have a large demand for ES such as water resources, green space recreation, and biodiversity protection. The increase of population density also leads to increased pressure on the supply of ES. With the advancement of urbanization and industrialization, land use intensity has increased significantly in the eastern part of Gansu Province, especially in Lanzhou and its surrounding areas. The increase in land use intensity has led to a decrease in the supply of ES, such as the reduction of green space and the destruction of biological habitats. These changes have a direct impact on the demand pattern of ES. This is particularly the case with respect to land resource management and environmental quality improvement (Figure 3).

The pattern of ES demand in Gansu Province shows obvious regional differences. Lanzhou City and its surrounding areas have a high level of economic development and large population density, and the demand for ES such as water resources, green space leisure and air quality improvement is particularly prominent. Other economically developed small and medium-sized cities in Gansu province, such as Tianshui City and Zhangye City, etc. These cities are also facing demands for ES similar to those in Lanzhou, which need to balance ecological protection and resource utilization while pursuing economic development. The province has a number of nature reserves and ecologically sensitive areas, and the demand for ES in these areas is mainly reflected in biodiversity conservation, water conservation, and soil conservation. Gansu Province is rich in tourism resources, such as Mogao Grottoes in Dunhuang and Zakana in Gannan, etc. The demand for ES in these regions is mainly reflected in historical and cultural protection, tourism environment improvement and ecotourism development, etc. With the development of tourism, the demand for ES in these regions will further increase. In the agricultural concentrated areas of Gansu Province, such as the Hexi Corridor, the demand for ES is mainly reflected in soil conservation, water resource supply and agricultural biodiversity protection, etc. With the advancement of agricultural modernization, the demand for efficient water-saving irrigation technology, soil improvement and agro-ecological protection in these areas is also rising. To sum up, the potential demand for ES in Gansu Province is mainly concentrated in cities with fast economic development, ecologically sensitive areas, regions rich in tourism resources and areas concentrated in agriculture. The demand for ES in these regions reflects the urgency of seeking a balance between economic and cultural development and ecological protection in Gansu Province.

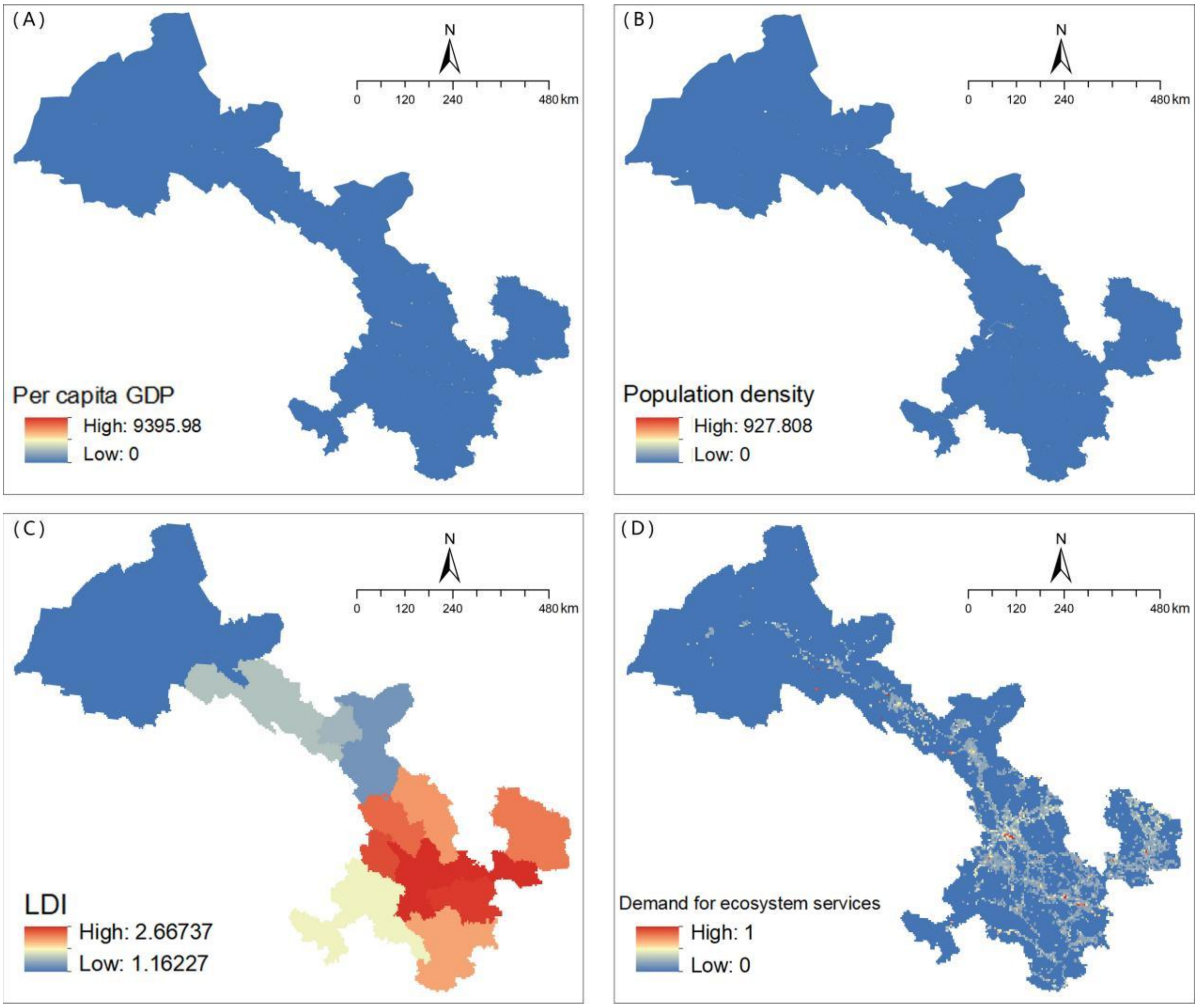

Figure 3. Demand pattern of ES in Gansu

3.3. Coupling coordination relationship between environment and cultural services

From the perspective of the region as a whole, the environment-culture coupling coordination degree of Gansu Province shows obvious differences in different terrain and urban areas, and the overall coupling coordination degree is general. The western plateau region shows a high coupling coordination degree because of its rich natural resources and cultural landscape. On the other hand, the coupling coordination degree of the Loess Plateau and river valley in the southeast is relatively low due to the influence of urbanization and industrialization (Figure 4).

In terms of spatial distribution, the western plateau area of Gansu Province, such as the Qilian Mountains and its surrounding plateau area, has a significant vertical ecological gradient and rich biodiversity due to its high altitude and abundant precipitation, which provides good natural conditions for environmental services. The natural ecosystems of these regions not only provide a rich material basis for cultural services, such as historical sites and folk customs, but also provide good ecological conditions for the supply of environmental services. These areas generally have relatively intact ecosystems and rich biodiversity, while retaining a greater cultural heritage and traditional way of life.

The Loess Plateau and river valley areas in the southeast of Gansu Province, such as Lanzhou and its surrounding areas, are relatively fragile because of flat terrain, high population density, high urbanization and industrialization. The degree of coupling coordination between environmental service and cultural service is relatively low. In the process of pursuing economic development, these regions have caused damage to the ecological environment to a certain extent, resulting in a decrease in the supply of environmental services. At the same time, with population growth and economic development, the demand for cultural services is increasing, but the supply is not growing at the same time, resulting in a decrease in the degree of coordination between environmental and cultural services.

The transition region is usually located between the high coupling coordination degree region and the low coupling coordination degree region. These regions have complex topography, such as the transition zone from plateau to plain, or the junction of ecologically sensitive area and economic development area. For example, in the transition zone from the Qilian Mountains to the Loess Plateau, and along the Silk Road Economic Belt. There are rich natural resources and relatively developed agriculture and industry here, which is an important channel connecting the east and west of Gansu Province. These regions are facing the double pressure of ecological protection and economic development and need to rationally plan and use cultural resources while protecting the ecological environment, so as to realize the sustainable development of environment and culture.

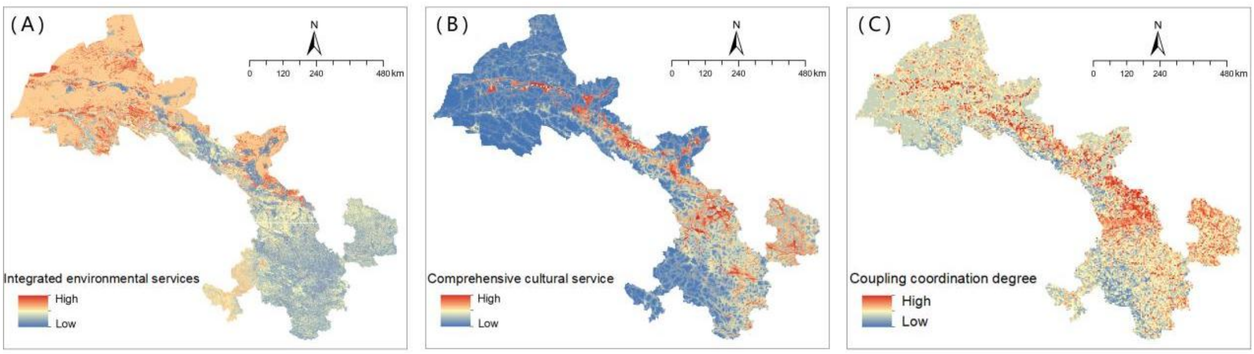

Figure 4. Analysis of the coordination degree of environment-culture coupling in Gansu Province

3.4. Analysis of supply-demand relationship of ES

The analysis of the supply-demand ratio of ES in Gansu Province reveals the supply-demand situation of different ES. According to the supply-demand ratio chart generated by ArcGIS (Figure 5), the supply-demand ratio of ES in Gansu Province can be divided into four main types: high supply-high demand, high supply-low demand, low supply-high demand, and low supply-low demand.

High supply-high demand area: In the plain area along the Yellow River in Gansu Province, especially in Baiyin, Dingxi, Tianshui and other places east of Lanzhou City, the supply of water production services thanks to the abundant water resources of the Yellow River and its tributaries is high. At the same time, due to the dense population and developed agriculture in this region, the demand for water resources is correspondingly high. However, overexploitation and use of water resources has led to a contradiction between supply and demand, especially during the dry season. In order to maintain the balance between supply and demand of water resources in this region, it is necessary to implement strict water management and water-saving measures and improve the efficiency of water resources use. In the agricultural areas of Gansu Province, such as the Yellow River coastal plain, Taohe River basin, Hexi Corridor, Longnan area, Qingyang area, etc., the supply of soil conservation services is higher, which is related to the widespread implementation of soil and water conservation measures in this area. These measures have effectively reduced soil erosion and increased the productivity of the land. With the advancement of agricultural modernization, the demand for soil conservation is also growing, and there is a need to further promote and optimize soil conservation techniques, while strengthening the protection and restoration of agro-ecosystems.

High-supply-low demand areas: In the Hexi Corridor region of Gansu Province, these ecosystems play an important role in carbon sequestration thanks to the high supply of carbon sequestration services in the vast deserts and grasslands of the region. But because the population is sparse, demand for carbon sequestration services is relatively low. In order to improve the efficiency of the use of these ES, ecotourism can be considered, while market-based mechanisms such as carbon sink trading can be strengthened to encourage local residents and governments to participate in the protection and use of carbon sequestration services. In the marginal areas of the Qinghai-Tibet Plateau in Gansu Province, such as the Qilian Mountains and the Gannan Plateau, these areas have a relatively fragile ecological environment due to their high altitude and cold climate, but they also have unique biodiversity and natural landscapes. In these areas, water conservation, habitat quality, soil conservation, aesthetic landscape and so on have a high supply. Due to the small population, poor transportation and low level of economic development, the demand for these ES by local residents is relatively low. In addition, due to the remoteness of these areas, the number of external tourists and resource users is also limited, leading to low demand for ES. In order to protect these precious ecosystems, ecological protection policies need to be strengthened, while public awareness of the value of ES needs to be raised through scientific research and educational activities.

Low supply - high demand areas: In the capital city of Lanzhou and other large cities such as Tianshui City, Zhangye City, Wuwei City, Jiuquan City and Baiyin City, due to the concentrated population and frequent economic activities, these urban areas have a high demand for ES, especially in the aspects of history and culture, regional culture, recreation and aesthetic landscape, etc., due to the ecological environment pressure accompanying the process of urbanization, The urban green space and leisure facilities in these cities cannot fully meet the needs of residents, and the supply is relatively low. In addition, these regions have rich historical sites and cultural traditions, but due to the insufficient protection of cultural heritage in the process of urbanization, the supply of historical culture and regional cultural services is limited. In order to meet residents' high expectations and demands for cultural entertainment, leisure activities, green parks and protection of historical sites, it is necessary to fully consider the construction of green space system and leisure facilities in urban planning, encourage residents to participate in outdoor activities and ecological tourism, and strengthen the protection and restoration of cultural heritage through cultural activities and tourism development. Improve the accessibility and attractiveness of these services.

Low supply - low demand areas: In some remote mountain areas of Gansu Province, such as Dibu County and Luqu County of Gannan Tibetan Autonomous Prefecture, Hezheng County and Dongxiang County of Linxia Hui Autonomous Prefecture, Min County and Zhang County in the west and south of Dingxi City, Wen County and Zhangjiachuan County of Longnan City and Zhangjiachuan County of Tianshui City, etc. These regions are of remote geographical location with perennial drought and little rain and low vegetation coverage rate. The blind and disorderly urbanization process has led to lagging infrastructure construction, relatively low level of economic development, and limited living standards of residents, so the ecological supply services in these areas are low. However, due to the limited population and economic development, the lack of universal ecological education and policy guidance, little attention is paid to the needs of carbon sequestration services in the development process, and the resources are not fully utilized. In order to promote the sustainable development of these areas, the development of ecotourism can be considered, while strengthening the construction of infrastructure to improve the living standards of local residents.

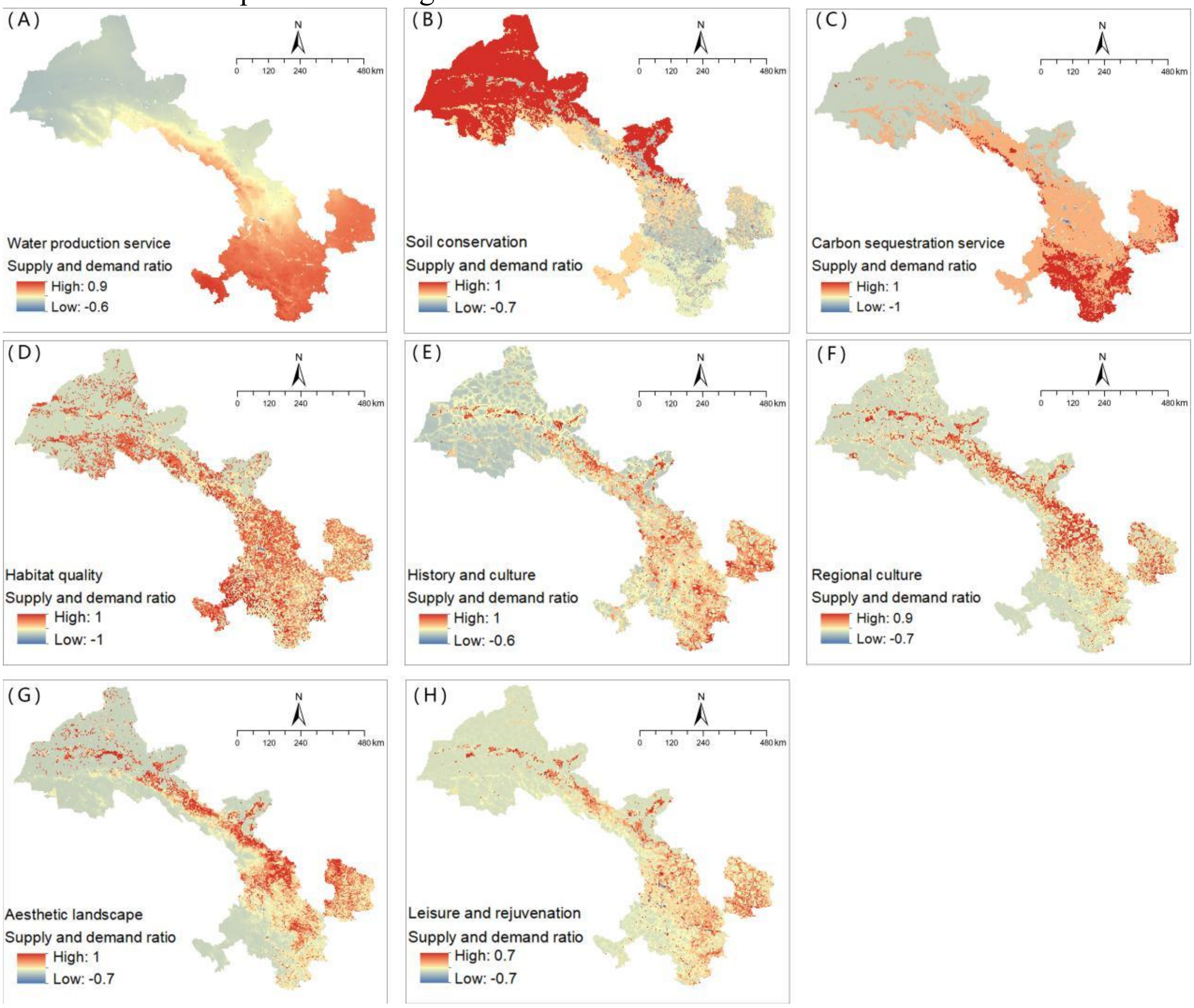

Figure 5. Distribution of ES supply and demand in Gansu Province

3.5. Spatial distribution characteristics of ESF

The study on the measurement and spatial distribution characteristics of ESF is based on the spatial matching results of ES supply and demand, and the spatial distribution information of ES supply and demand is extracted by using the hot spot analysis in ArcGIS software. The hot spot ≥

95% is the supply area, and the cold spot ≥ 95% is the demand area. Considering the effect of patch area size on the overall supply and demand pattern of the study area, the continuous patch with an area greater than 1km² was selected as the supply and demand area based on the actual situation of the study area. A resistance surface model (Figure 6) was further constructed to quantify and simulate barriers to the flow of ES, such as terrain, land use, and transportation networks. Based on circuit theory, this paper analyzes the transmission and distribution of service flows in ecosystem networks, and identifies the key ecological connectivity regions, which play a decisive role in maintaining the continuity and efficiency of ES.

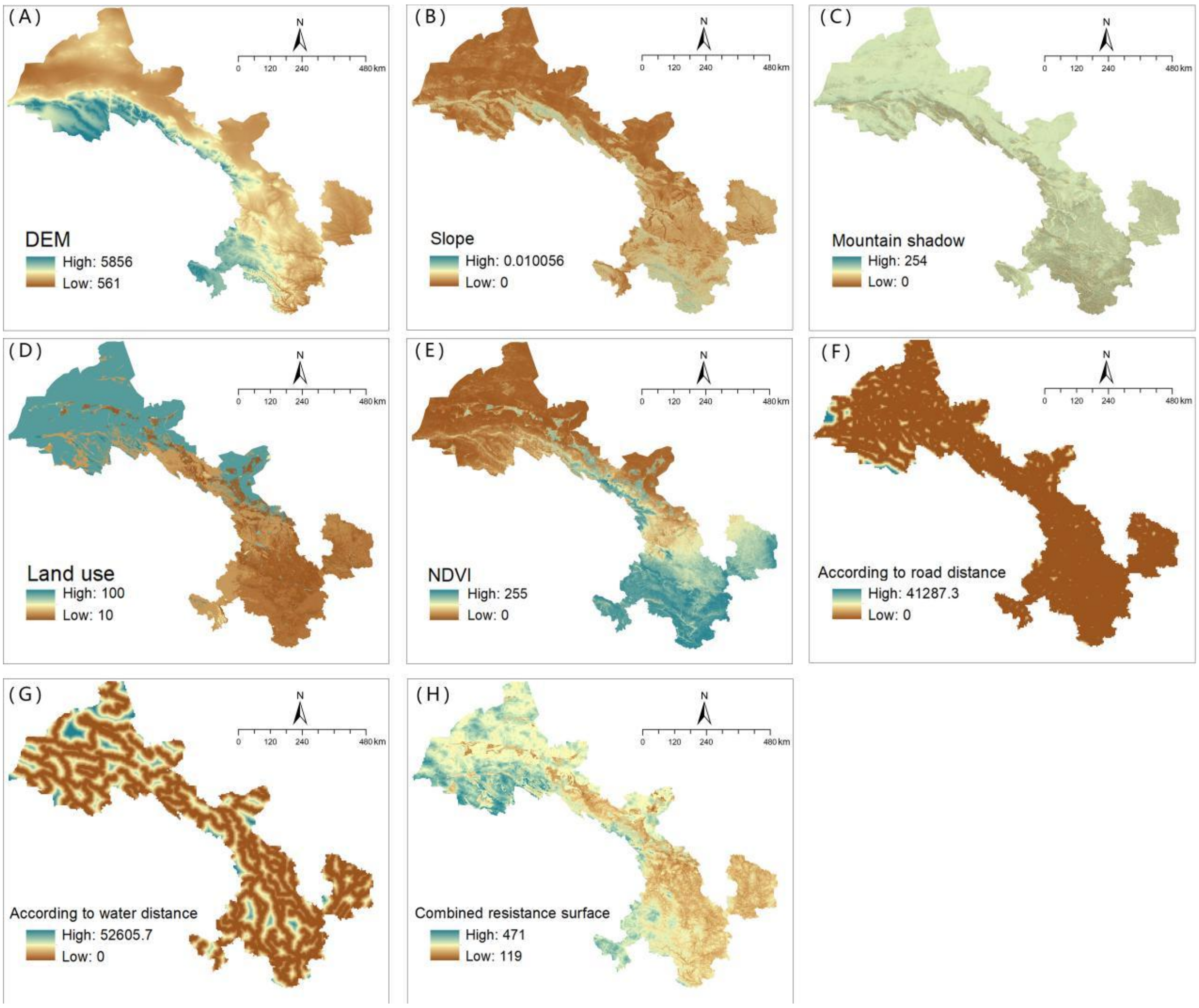

Figure 6. Construction of ecological resistance surface in Gansu Province

The analysis of ESF in Gansu Province revealed the distribution characteristics of supply and demand sources of different ES and the flow characteristics of service flows in the province. The eight charts generated by LinkageMapper showed the supply and demand relationship and connectivity of different ES. Different types of ES will be analyzed in terms of spatial distribution, transfer mechanism, flow path, and service value (Figure 7). Environmental service flow:

Water production and service flow supply areas are usually located in the Qilian Mountains and the upper reaches of the Yellow River in Gansu Province, such as Liujiaxia, Baiyin and other places (Figure 7A). These areas are important water conservation areas because of the large volume of glacier snow mountains and rivers. Demand areas are mostly distributed in the plain areas along the Yellow River, such as Lanzhou, Baiyin and other cities, as well as agricultural and industrial areas, such as Tianshui, Wuwei, Jiayuguan and other cities. These areas are densely populated and have high industrial and agricultural water demand. Water resources are transferred from the supply area to the demand area through natural and artificial channels such as rivers and irrigation systems. The transfer of water resources in Gansu Province is affected by topographic and climatic conditions, such as seasonal precipitation and seasonal changes of rivers. The flow path of water resources mainly follows the Yellow River and its tributaries, as well as artificial diversion channels, which are characterized by natural flow from high altitude to low altitude. Water resources supply is of vital value to ensure agricultural production, urban water supply and ecological balance in Gansu Province. Proper management and protection of water supply areas are crucial to maintaining water security throughout the province.

The supply areas of soil conservation service flow are mainly located in erosion-prone areas such as the Loess Plateau in the eastern part of Gansu Province (Figure 7B). In these areas, soil loss is reduced through vegetation cover and soil and water conservation measures. Demand areas include peri-urban areas and transportation arteries, the Yellow River and its tributaries, and agricultural areas where soil erosion needs to be prevented and land quality improved. The transfer of soil conservation services is mainly achieved by implementing soil and water conservation projects, vegetation restoration and other measures. Soil conservation service flows are mostly small-scale flows, and their paths are reflected in the implementation areas of soil conservation measures, such as terraces, slope protection, vegetation belts, etc. Soil conservation services play an important role in ensuring agricultural production, preventing soil erosion and maintaining ecological balance, and these services are crucial to the food security and ecological security of Gansu Province.

The regions with hot and cold spots ≥95% of carbon sequestration services are too few to form a service flow (Figure 7C). This is because the main ecosystem types in Gansu Province are desert and grassland, and there are few forests and wetlands with high carbon sequestration capacity, and their carbon sequestration capacity is low. Coupled with agricultural expansion, urbanization and industrial development, ecological fragmentation and lack of continuity between supply and demand regions are no longer analyzed for carbon sequestration service flows.

Habitat quality service flow supply areas are usually located in ecological reserves, national parks and nature reserves, such as Zhangye National Wetland Park and Qilian Mountain Forest in Gansu Province (Figure 7D). Demand areas include urban and densely populated areas, degraded areas affected by human activities such as overgrazing, agricultural expansion and mining, and biodiversity hotspots requiring protection such as Kongtong Mountain Nature Reserve and forests and grasslands in Sunan region. The transfer of habitat quality service flow is mainly achieved through ecological restoration projects and conservation measures, such as afforestation and wetland restoration. The natural flow path of habitat quality service flow is mainly distributed along rivers and river systems and topographic gradients. The connecting areas between ecological corridors and nature reserves provide the transmission channel of habitat quality service. Transportation networks and ecological restoration projects constitute the flow paths of human intervention; In addition, ecotourism and environmental education activities promote the socio-economic mobility of habitat quality services; Government policy support provides management and planning guidance for service flows. Habitat quality services are important for maintaining ecosystem health, protecting biodiversity and providing recreational space. These services play a positive role in improving the quality of life of the population and promoting sustainable development.

Cultural service flow:

The supply area of historical and cultural services is mainly concentrated in the areas with important historical sites and cultural attractions, such as Dunhuang, Jiayuguan, Tianshui and so on (Figure 7E). Demand areas include cities and tourist destinations that are heavily visited by domestic and foreign tourists. The historical and cultural services are transferred from the supply area to the demand area through tourism, education and cultural exchanges. The rich cultural heritage of Hexi Corridor makes the services highly accessible, and they are more widely recognized and utilized through tourism promotion and cultural communication activities. The flow of historical and cultural services is mainly routed through transport networks, especially road, rail and air routes connecting major cities and cultural attractions. Historical and cultural services have significant value in promoting local economic development, enhancing cultural identity and enhancing social well-being. Protecting and inheriting these cultural heritages is crucial to the soft power and international image of Gansu Province and the country.

Regional cultural service flow supply areas are located in areas with rich cultural heritage and folk activities, such as Gannan Tibetan Autonomous Prefecture and Linxia Hui Autonomous Prefecture in Gansu Province, which have unique ethnic customs, religious architecture, traditional festivals and handicrafts (Figure 7F). Demand areas include groups that have a need for these cultural resources, such as local residents, domestic and foreign tourists, cultural researchers and educational institutions. The transfer of regional cultural services is mainly realized through cultural exchange activities, educational projects, tourism promotion and media communication. The routes of service flow include cultural and educational centers, museums, art galleries, traditional villages and cultural sites, etc. Modern communication technology and the Internet also provide new channels for the dissemination of regional culture, making cultural service flow no longer limited to the flow of physical space. Regional cultural services are of great value in maintaining national cultural identity, promoting social harmony, enhancing regional attractiveness and improving the quality of life of residents, contributing to the preservation of cultural diversity and supporting local economic development.

The supply area of leisure and entertainment service flow is mainly distributed in areas rich in natural landscapes and cultural attractions and supporting services around scenic spots, such as Mogao Grottoes in Dunhuang and Maiji Mountain in Tianshui, while the demand area includes urban residents and tourists in nearby cities (Figure 7G). Through the development of tourism and the organization of leisure activities, leisure and recreation services are transferred from the supply area to the demand area. The routes of the service flow include natural landscape tourism routes, such as the grassland scenery of Gannan, the forest and snow mountains of Qilian Mountains, etc. Cultural sites such as the Great Wall site at Jiayuguan; Festival activities such as Lanzhou Yellow River Cultural Tourism Festival, Tianshui Fuxi Festival and so on; Rural tourism paths such as farm music, folk experience, etc. Leisure and recreation services are of great value for improving residents' quality of life, promoting local economic development and protecting cultural heritage.

The aesthetic landscape service flow supply area is located in the parks and natural scenery that bring people aesthetic spiritual enjoyment, such as Zhangye Danxia landform, Dunhuang Mingsha Spring, grasslands, lakes, temples and Tibetan culture in Gannan Tibetan Autonomous Prefecture (Figure 7H). The demand areas are large cities with concentrated population in the province, such as Lanzhou and Tianshui, as well as universities and research institutions in the province that have research and education needs for aesthetic landscape resources. Aesthetic landscape service is transferred from the supply area to the demand area through tourism promotion and cultural communication. Flow paths may include tourist routes, cultural exchange activities, educational projects, etc., which transfer aesthetic landscape resources from the supply area to the demand area. In order to promote the effective flow of aesthetic landscape service flow, it is necessary to strengthen the protection and reasonable development of landscape resources, improve the quality of tourism services, develop cultural and educational projects, and strengthen tourism publicity and marketing. Aesthetic landscape service is of great value to enhance regional image, attract tourism investment and promote cultural inheritance.

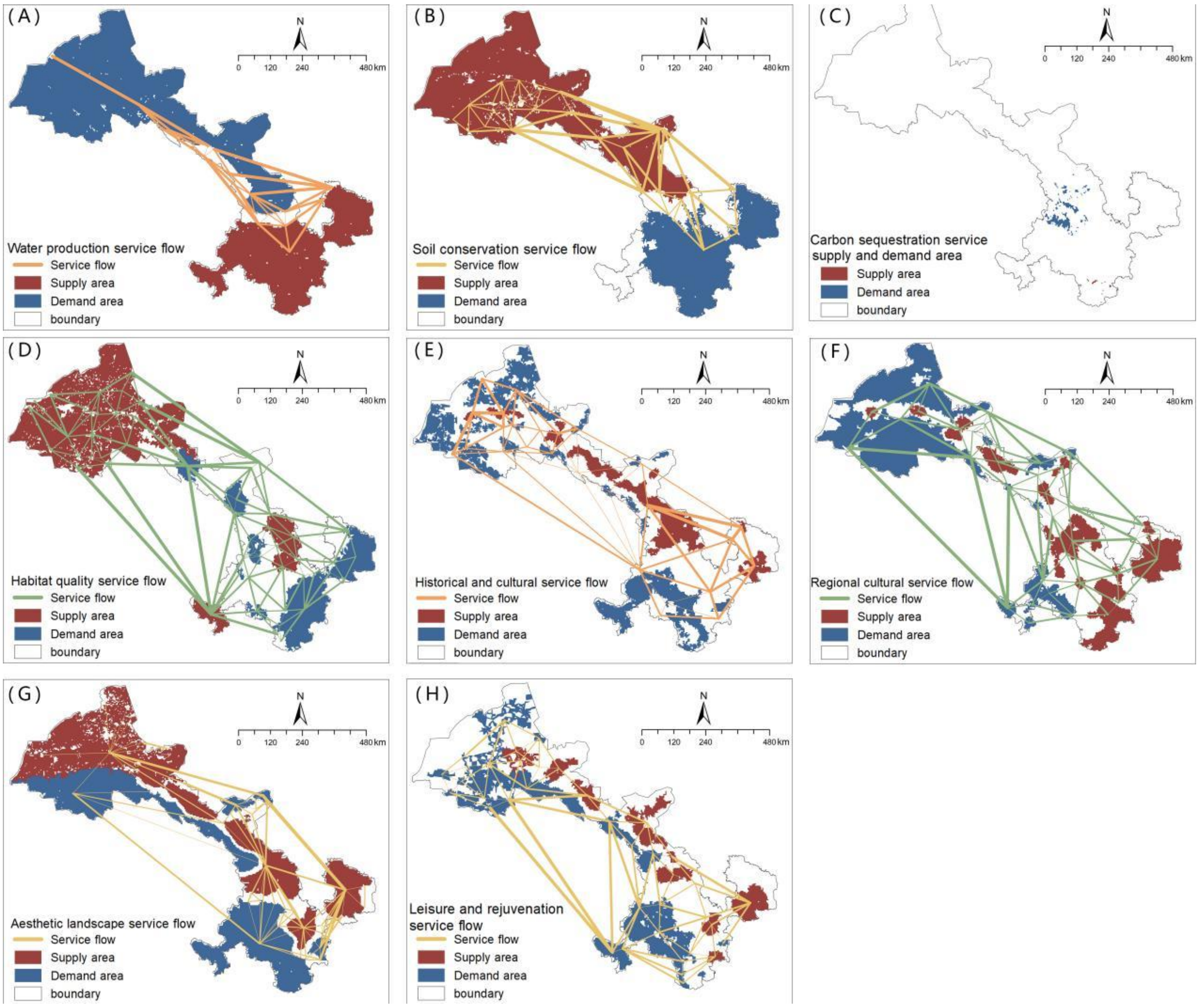

Figure 7. ESF pattern in Gansu Province

4. Ecological function zoning and optimization strategy

Based on the comprehensive consideration of ES supply and demand pattern, environment-culture coupling analysis, supply-demand ratio analysis and ESF pattern, the ecological function zoning of Gansu Province was divided. First, according to the number of cold and hot categories of each service and the status of comprehensive service flow, The reclassification tool of ArcGIS was used to encode important and non-important regions (Xu, et al.,2019). The important region code was 1, and the non-important region code was 0. The region with more than two important regions is assigned code 2, indicating a large number of regions; code 0 is assigned to regions that are less than or equal to two important regions, indicating a smaller number of regions (Table 4). Based on this, an integrated ES and ecological function zoning system was constructed, and Gansu Province was divided into three main regions: ecological culture protection zone, ecological culture maintenance zone and ecological culture development zone (Figure 8). Corresponding management countermeasures were proposed for each management zone.

Table 4. Ecological function zoning system table

8 service supply and demand ratio of cold hot spots	Preliminary zoning	Comprehensive service flow status	Ecological management zone

Cold point (< 0)	Ecological demand area	1 demand cold spot or more	Ecological culture reserve
		0 demand cold spots /0 supply hot spots	Ecological culture maintenance area
Hot Spots (> 0)	Ecological supply area	Contains more than 1 supply hotspot	Ecological culture development zone

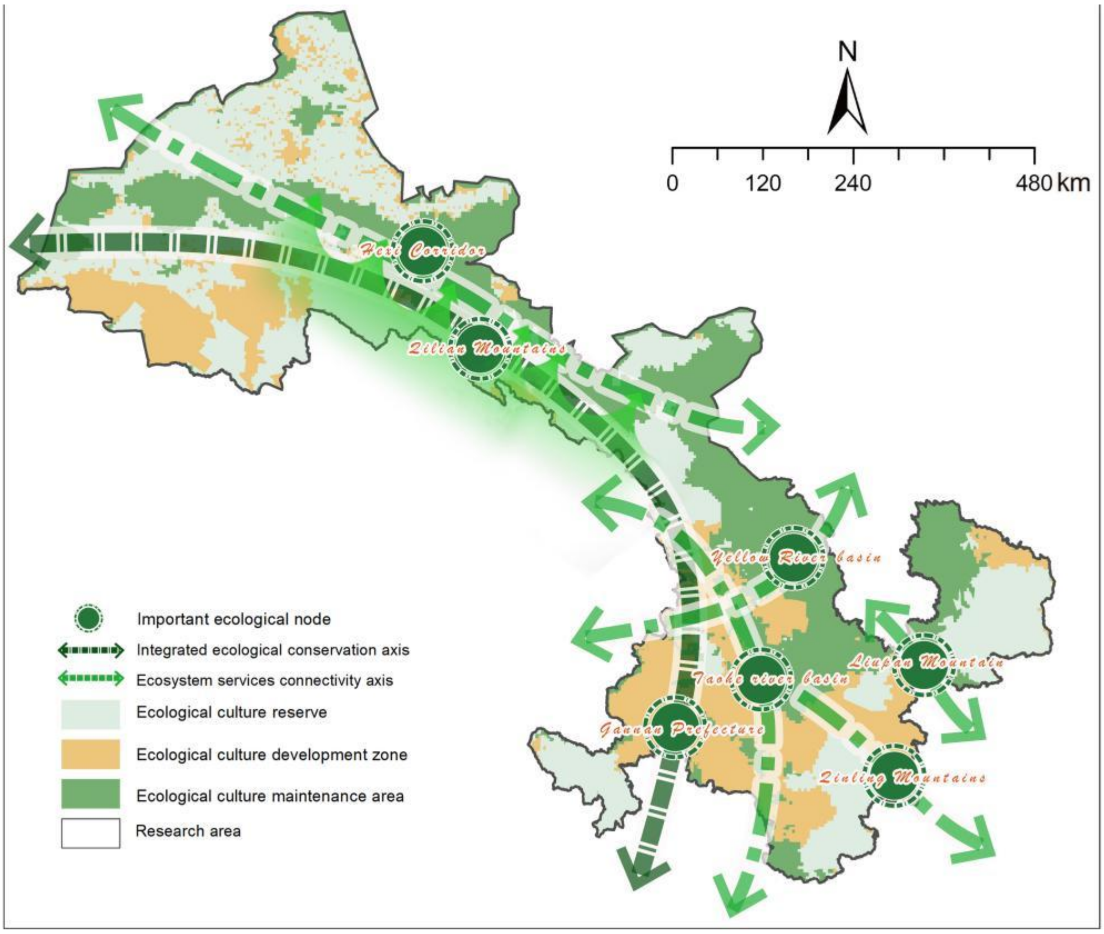

Figure 8. Ecological function zoning in Gansu Province

Ecological and cultural reserves: This region is mainly located in the Qilian Mountains, Gannan Plateau, Qinling Mountains and other regions of Gansu Province. These regions are rich in natural resources and unique ecological environment and are important protected areas of biodiversity. The coupling and coordination degree of environmental services and cultural services is high. The natural ecosystems of these regions provide a rich material basis for cultural services, such as historical sites and folk customs. First, strict ecological protection measures should be implemented to limit development activities and ensure the integrity of key ecosystems and cultural heritage, such as the establishment of nature reserves and national parks, and the strengthening of protection of key ecological areas such as the Qilian Mountains. Second, ecotourism should be encouraged and supported, such as the development of low-impact hiking trails, ecological education and cultural experience programs. Use natural landscapes and cultural heritage to attract visitors, while ensuring that the impact of tourism activities on the ecological environment is minimized. Finally, local communities should be encouraged to participate in ecological protection and cultural inheritance, using traditional knowledge and practices for ecological management, for example, supporting local residents to participate in ecological monitoring projects, protecting and inheriting traditional agriculture and lifestyle closely related to the local ecological environment, so as to achieve the purpose of ecological and cultural protection.

Ecological culture maintenance area: Ecological and cultural maintenance areas are mainly distributed in Taohe River Basin, Liupanshan, Hexi Corridor and other areas in Gansu Province. In the process of pursuing economic development, these areas are faced with the challenges of ecological environment protection and resource utilization. The supply-demand ratio analysis of ES in ecological and cultural maintenance areas shows that there is an imbalance between supply and demand in some services such as water production services and soil conservation. It is necessary to take effective measures for ecological protection and restoration. The establishment of ecological cultural conservation areas aims to reduce the pressure on the ecosystem through ecological restoration and resource management, firstly by implementing ecological restoration projects such as returning farmland to forest, soil and water conservation projects, as well as optimizing land use planning and sustainable agricultural practices to reduce the demand for water resources. Secondly, promote the innovation and development of cultural services through cultural creative industries and cultural experience projects, such as the development of art works, handicrafts and cultural festivals themed on local culture, in order to improve the supply of cultural services. Finally, support the development of green industries and circular economy, encourage enterprises to adopt environmental protection technologies and clean production methods, develop green buildings and renewable energy industries, and reduce the negative impact on the environment.

Ecological Culture Development Zone: Eco-cultural development zones are concentrated in urban areas of Gansu Province, especially Lanzhou City, Tianshui City and their surrounding areas. These regions have a high level of economic development and large population density, and the demand for ES is particularly urgent. The analysis of ESF in eco-cultural development zones reveals the extensive coverage and rich flow channels of cultural service flow. It shows that these regions have great potential in the supply of cultural services, and the establishment of eco-cultural development zones aims to promote the coordinated development of eco-culture through reasonable land use planning and ecological protection measures. Within the eco-culture development zone, priority should first be given to the development of green infrastructure, such as urban green space systems, ecological corridors and public transport networks, to support an eco-friendly urban development model. Secondly, we should promote the deep integration of culture and ecology, integrate cultural elements into ecological space through urban renewal and architectural design, such as the construction of cultural parks and ecological art districts, and improve the quality of life of urban residents. Finally, incentive policies should be formulated to encourage the public to participate in ecological protection and cultural inheritance activities. For example, tax incentives and financial support should be provided to those enterprises and individuals who have made contributions to ecological protection and cultural inheritance. At the same time, public education and publicity activities should be carried out to raise the public's awareness of environmental protection, so as to promote the sustainable development of ecological, cultural and economic aspects.

5.Discussion

1) Through a comprehensive analysis of the supply and demand pattern of ES in Gansu Province, this paper applies a variety of methods and models, such as InVEST model, MaxEnt model and coupling coordination degree model, to conduct a quantitative assessment of the supply and demand of ES. The research strategy of multi-method integration improves the scientificity and accuracy of assessment results and provides powerful decision support for ecological protection and resource management. However, research on ES supply and demand

still faces some challenges. For example, the quantitative method of service demand is not perfect, especially for the demand assessment of non-material services such as cultural services, there is a lack of unified and systematic evaluation system (Brown, et al.,2016). Secondly, the dynamic changes and trade-offs of ES have not been fully paid attention to. ES are not static, and they change with time, environmental changes and socio-economic development (Wu, et al.,2019). Therefore, future research needs to incorporate the assessment of environmental and cultural ecosystem services into long-term planning, exploring more scientific and comprehensive evaluation methods to better quantify and assess the value of cultural ecosystem services. Qualitative and quantitative research methods can be combined, such as expert interviews, questionnaires, and field surveys, to gain a deep understanding of the specific manifestations and value perceptions of cultural services and aesthetic values in different regions and among various groups. At the same time, the research findings from other fields, such as cultural economics and environmental psychology, can be drawn upon to apply relevant theories and models to the assessment of ecosystem services, thereby enhancing the accuracy and comprehensiveness of the evaluation (Harwood, et al.,2015).

2) This paper is innovative in the measurement of ESF. Through the application of LinkageMapper tool and circuit theory, a spatial flow model of ESF is built. The research conclusions based on this method not only reveal the spatial distribution characteristics of service flow, but also provide key information for ecological protection and restoration. However, current research methods still face some challenges and limitations. For example, circuit theory provides a powerful analytical framework for ESF, but the complexity of the model may lead to simplification of the interactions within the ecosystem and may not fully capture all the factors affecting service flow (Xu, et al.,2024). And existing models often lack sufficient consideration of the dynamic characteristics of ES over time, which limits our understanding of long-term trends in service flows. Future studies on ESF need to be expanded and deepened in multiple aspects. First, more factors such as climate change and human activity intensity can be included in the model to improve the accuracy of service flow prediction (Urbina-Cardona, et al.,2023). Secondly, the quantitative method of service flow needs to be further optimized, especially in the aspects of flow calculation and path optimization, which will help to realize the efficient use of service flow and maximize ecological protection. In addition, interdisciplinary integration will also be the key to future development. By combining the theories and methods of ecology, geography, sociology, economics and other disciplines (Gao, et al.,2023), a more comprehensive analytical framework can be formed, which is essential for building a more comprehensive and adaptable management system.

3) According to the ecological function zoning strategy proposed in this paper, Gansu Province is divided into ecological culture protection area, ecological culture maintenance area and ecological culture development zone based on the analysis results of ES supply and demand ratio, environment-culture coupling coordination degree and ESF. This zoning method is scientific and practical and helps to guide the ecological protection and sustainable development of Gansu Province. However, the implementation of ecological function zoning needs to be closely combined with the territorial spatial planning of Gansu Province to ensure the implementation of the zoning strategy. Future improvement directions include: (1) Strengthening the connection between zoning strategies and local policies: Ecological function zoning strategies should be coordinated with local policies, development plans and laws and regulations of Gansu Province to ensure that the results of zoning can be translated into specific management measures and action plans. This includes the integration with land use planning, environmental protection regulations, urban and rural construction planning and other policies (Duan, et al.,2021), as well

as communication and collaboration with relevant departments to form a complete set of policy support system; (2) Establish a Long-term Dynamic Monitoring Mechanism: Regularly collect and update data related to ecosystem services, including data on intangible ecosystem services. Utilize remote sensing technology, Geographic Information Systems (GIS), and socio-economic data to analyze the trends and driving factors of ecosystem services over time and space, identifying key evolution points and influencing factors. On this basis, construct a dynamic evolution model of ecosystem services to predict their evolution trends under different future scenarios, providing a scientific basis for long-term planning (Walsh, et al.,2016); (3) Promoting cross-regional cooperation: The implementation of ecological functional zoning requires cross-regional cooperation, especially in the protection of ecologically sensitive areas and ecological corridors (Li, et al.,2024). Through the establishment of inter-regional cooperation mechanisms, ecological connectivity should be strengthened, ecological protection and restoration work should be jointly promoted, and resource sharing and ecological benefits should be maximized. This may involve coordination mechanisms across administrative divisions, as well as cooperation with neighboring provinces to jointly build ecological security barriers (Li, et al.,2023). Through these improvements, the ecological function zoning of Gansu Province will be more scientific and reasonable, providing a solid foundation for realizing regional ecological security and sustainable development.

6. Conclusion

The supply and demand pattern of ES in Gansu Province showed significant regional differences. The western region, especially the Qilian Mountains, is an important water conservation area and carbon sequestration service supply area because of its high altitude and abundant precipitation. While the eastern region, such as the Loess Plateau and river valley, is facing the problem of insufficient supply of water production services, it is outstanding in the supply of cultural services and has rich historical sites and cultural landscapes. The supply-demand ratio analysis revealed the imbalance between supply and demand in water resources, soil conservation, habitat quality and aesthetic landscape in Gansu Province, especially in densely populated areas with rapid economic development, the demand for ES is more urgent.

The coupling coordination degree of environmental and cultural services in Gansu Province shows obvious differences in different terrain and urban areas. Because of its rich natural resources and cultural landscape, the western plateau region shows a high degree of coupling and coordination. On the other hand, the coupling coordination degree of Loess Plateau and river valley in the southeast is relatively low due to the influence of urbanization and industrialization. This shows the need for better coordination and balance between ecological and environmental protection and cultural inheritance in the pursuit of economic development.

The analysis of ESF shows that environmental service flow and cultural service flow in Gansu Province show different flow paths and connectivity. Water production service flows mainly along the Yellow River and its tributaries, while historical and cultural service flows are transmitted between different regions through tourist routes and cultural exchange activities. The flow of habitat quality services is affected by natural and human factors and needs to be optimized by ecological restoration and protection measures. The aesthetic landscape service flow depends on tourism promotion and cultural communication, as well as policy support and marketing.

Based on the analysis results of ES supply and demand ratio, environment-culture coupling coordination degree and ESF, Gansu Province is divided into ecological culture protection area, ecological culture maintenance area and ecological culture development zone. Ecological and cultural reserves are mainly located in areas rich in natural resources and cultural landscapes, and strict protection measures need to be implemented. The ecological culture maintenance area faces the challenge of ecological environment protection and resource utilization and needs to promote the coordinated development of ecological culture through ecological restoration and resource management. Ecological culture development zones are concentrated in urban areas, aiming to promote the coordinated development of ecological culture through rational land use planning and ecological protection measures. These zoning strategies need to be closely integrated with the territorial spatial planning of Gansu Province to ensure their effective implementation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Costanza R, de Groot R, Braat L, Kubiszewski I, Fioramonti L, Sutton P, Farber S, Grasso M, 2017. Twenty years of ecosystem services: How far have we come and how far do we still need to go?[J]. Ecosystem Services,28:1-16.

[2] Irfan M, Ullah S, Razzaq A, Cai J, Adebayo T S, 2023. Unleashing the dynamic impact of tourism industry on energy consumption, economic output, and environmental quality in China: A way forward towards environmental sustainability[J]. Journal of Cleaner Production,387:135778.

[3] Wang Z, Guo J, Ling H, Han F, Kong Z, Wang W, 2022. Function zoning based on spatial and temporal changes in quantity and quality of ecosystem services under enhanced management of water resources in arid basins[J]. Ecological Indicators,137:108725.

[4] Liu Q, Qiao J, Li M, Huang M, 2024. Spatiotemporal heterogeneity of ecosystem service interactions and their drivers at different spatial scales in the Yellow River Basin[J]. Science of The Total Environment,908:168486.

[5] Zeng J, Cui X, Chen W, Yao X, 2023. Ecological management zoning based on the supply-demand relationship of ecosystem services in China[J]. Applied Geography,155:102959.

[6] Xie G, Zhang C, Zhen L, Zhang L, 2017. Dynamic changes in the value of China ’ s ecosystem services[J]. Ecosystem Services,26:146-154.

[7] Vallet A, Locatelli B, Levrel H, Wunder S, Seppelt R, Scholes R J, Oszwald J, 2018. Relationships Between Ecosystem Services: Comparing Methods for Assessing Tradeoffs and Synergies[J]. Ecological Economics,150:96-106.

[8] Wang L, Zheng H, Chen Y, Ouyang Z, Hu X, 2022. Systematic review of ecosystem services flow measurement: Main concepts, methods, applications and future directions[J]. Ecosystem Services,58:101479.

[9] Bagstad K J, Johnson G W, Voigt B, Villa F, 2013. Spatial dynamics of ecosystem service flows: A comprehensive approach to quantifying actual services[J]. Ecosystem Services,4:117-125.

[10] Syrbe R, Walz U, 2012. Spatial indicators for the assessment of ecosystem services: Providing, benefiting and connecting areas and landscape metrics[J]. Ecological Indicators,21:80-88.

[11] Bayala J, Sanou J, Teklehaimanot Z, Kalinganire A, Ouédraogo S J, 2014. Parklands for buffering climate risk and sustaining agricultural production in the Sahel of West Africa[J]. Current Opinion in Environmental Sustainability,6:28-34.

[12] Li Q, Bao Y, Wang Z, Chen X, Lin X, 2024. Trade-offs and synergies of ecosystem services in karst multi-mountainous cities[J]. Ecological Indicators,159:111637.
[13] Brück M, Abson D J, Fischer J, Schultner J, 2022. Broadening the scope of ecosystem services research: Disaggregation as a powerful concept for sustainable natural resource management[J]. Ecosystem Services,53:101399.
[14] Chen Y, Xu F, 2022. The optimization of ecological service function and planning control of territorial space planning for ecological protection and restoration[J]. Sustainable Computing: Informatics and Systems,35:100748.
[15] Ding T, Chen J, Fang Z, Wang Y, 2023. Exploring the differences of ecosystem service values in different functional areas of metropolitan areas[J]. Sustainable Production and Consumption,38:341-355.
[16] Wu J, Fan X, Li K, Wu Y, 2023. Assessment of ecosystem service flow and optimization of spatial pattern of supply and demand matching in Pearl River Delta, China[J]. Ecological Indicators,153:110452.
[17] Li P, Liu C, Liu L, Wang W, 2021. Dynamic Analysis of Supply and Demand Coupling of Ecosystem Services in Loess Hilly Region: A Case Study of Lanzhou, China[J]. Chinese Geographical Science,31(02):276-296.
[18] Liao W, 2022. Temporal and spatial variations of eco-environment in Association of Southeast Asian Nations from 2000 to 2021 based on information granulation[J]. Journal of Cleaner Production,373:133890.
[19] Fei D, Cheng Q, Mao X, Liu F, Zhou Q, 2017. Land use zoning using a coupled gridding-self-organizing feature maps method: A case study in China[J]. Journal of Cleaner Production,161:1162-1170.
[20] Wang J, Liu B, Zhou T, 2023. The category identification and transformation mechanism of rural regional function based on SOFM model: A case study of Central Plains Urban Agglomeration, China[J]. Ecological Indicators,147:109926.
[21] Dahan K S, Kasei R A, Husseini R, Sarr M, Said M Y, 2024. Analysis of the future potential impact of environmental and climate changes on wildfire spread in Ghana's ecological zones using a Random Forest (RF) machine learning approach[J]. Remote Sensing Applications: Society and Environment,33:101091.
[22] Zhang Z, Hu B, Jiang W, Qiu H, 2023. Spatial and temporal variation and prediction of ecological carrying capacity based on machine learning and PLUS model[J]. Ecological Indicators,154:110611.
[23] Ghosh S, Das Chatterjee N, Dinda S, 2021. Urban ecological security assessment and forecasting using integrated DEMATEL-ANP and CA-Markov models: A case study on Kolkata Metropolitan Area, India[J]. Sustainable Cities and Society,68:102773.
[24] Lu Y, Li Y, Fang G, Deng M, Sun C, 2023. Ecological risk assessment and management for riverfront development along the Yangtze River in Jiangsu Province, China[J]. Ecological Indicators,155:111075.
[25] Yang Y, Feng Z, Wu K, Lin Q, 2022. How to construct a coordinated ecological network at different levels: A case from Ningbo city, China[J]. Ecological Informatics,70:101742.
[26] Xu Y, Zhao X, Huang P, Pu J, Ran Y, Zhou S, Zhao Q, Feng Y, Tang Y, Tao J, Zhang Y, 2024. A new framework for multi-level territorial spatial zoning management: Integrating ecosystem services supply-demand balance and land use structure[J]. Journal of Cleaner Production,441:141053.
[27] Wang W, Li B Y, Ren Z Y, 2017. Ecosystem service function evaluation: A case study of the yinchuan basin in China[J]. Ecological Engineering,106:333-339.

[28] Kong X, Han M, Li Y, Kong F, Sun J, Zhu W, Wei F, 2024. Spatial differentiation and formation mechanism of ecological sensitivity in large river basins: A case study of the Yellow River Basin, China[J]. Ecological Indicators,158:111571.
[29] An Y, Liu S, Sun Y, Shi F, Zhao S, Liu Y, Li M, 2022. A partitioning approach for regional sustainability based on economic development indicators and ecological values for China[J]. Journal for Nature Conservation,67:126179.
[30] Vári Á, Adamescu C M, Balzan M, Gocheva K, Götzl M, Grunewald K, Inácio M, Linder M, Obiang-Ndong G, Pereira P, Santos-Martin F, Sieber I, Stępniewska M, Tanács E, Termansen M, Tromeur E, Vačkářová D, Czúcz B, 2024. National mapping and assessment of ecosystem services projects in Europe – Participants' experiences, state of the art and lessons learned[J]. Ecosystem Services,65:101592.
[31] Campbell E, Marks R, Conn C, 2020. Spatial modeling of the biophysical and economic values of ecosystem services in Maryland, USA[J]. Ecosystem Services,43:101093.
[32] Felipe-Lucia M R, Soliveres S, Penone C, Manning P, van der Plas F, Boch S, Prati D, Ammer C, Schall P, Gossner M M, Bauhus J, Buscot F, Blaser S, Bluthgen N, de Frutos A, Ehbrecht M, Frank K, Goldmann K, Hansel F, Jung K, Kahl T, Nauss T, Oelmann Y, Pena R, Polle A, Renner S, Schloter M, Schoning I, Schrumpf M, Schulze E D, Solly E, Sorkau E, Stempfhuber B, Tschapka M, Weisser W W, Wubet T, Fischer M, Allan E, 2018. Multiple forest attributes underpin the supply of multiple ecosystem services[J]. Nat Commun,9(1):4839.
[33] Meng G, Wang K, Wang F, Dong Y, 2023. Analysis of the tourism-economy-ecology coupling coordination and high-quality development path in karst Guizhou Province, China[J]. Ecological Indicators,154:110858.
[34] Zhao Y, You W, Lin X, He D, 2023. Assessing the supply and demand linkage of cultural ecosystem services in a typical county-level city with protected areas in China[J]. Ecological Indicators,147:109992.
[35] Ding X, Jian S, 2024. Synergies and trade-offs of ecosystem services affected by land use structures of small watershed in the Loess Plateau[J]. Journal of Environmental Management,350:119589.
[36] Pittock J, Cork S, Maynard S, 2012. The state of the application of ecosystems services in Australia[J]. Ecosystem Services,1(1):111-120.
[37] Chen Z, Lin J, Huang J, 2023. Linking ecosystem service flow to water-related ecological security pattern: A methodological approach applied to a coastal province of China[J]. Journal of Environmental Management,345:118725.
[38] Li Y, Liu W, Feng Q, Zhu M, Yang L, Zhang J, Yin X, 2023. The role of land use change in affecting ecosystem services and the ecological security pattern of the Hexi Regions, Northwest China[J]. Science of The Total Environment,855:158940.
[39] Liu Z, Wang Y, Geng Y, Li R, Dong H, Xue B, Yang T, Wang S, 2019. Toward sustainable crop production in China: An emergy-based evaluation[J]. Journal of Cleaner Production,206:11-26.
[40] Zhang S, Wu T, Guo L, Zou H, Shi Y, 2023. Integrating ecosystem services supply and demand on the Qinghai-Tibetan Plateau using scarcity value assessment[J]. Ecological Indicators,147:109969.
[41] Sun R, Jin X, Han B, Liang X, Zhang X, Zhou Y, 2022. Does scale matter? Analysis and measurement of ecosystem service supply and demand status based on ecological unit[J]. Environmental Impact Assessment Review,95:106785.
[42] Yang Z, Zhan J, Wang C, Twumasi-Ankrah M J, 2022. Coupling coordination analysis and

spatiotemporal heterogeneity between sustainable development and ecosystem services in Shanxi Province, China[J]. Science of The Total Environment,836:155625.
[43] Li J, Jiang H, Bai Y, Alatalo J M, Li X, Jiang H, Liu G, Xu J, 2016. Indicators for spatial – temporal comparisons of ecosystem service status between regions: A case study of the Taihu River Basin, China[J]. Ecological Indicators,60:1008-1016.
[44] Hou Y, Li B, Müller F, Fu Q, Chen W, 2018. A conservation decision-making framework based on ecosystem service hotspot and interaction analyses on multiple scales[J]. Science of The Total Environment,643:277-291.
[45] Shen Z, Wu W, Tian S, Wang J, 2022. A multi-scale analysis framework of different methods used in establishing ecological networks[J]. Landscape and Urban Planning,228:104579.
[46] Wei B, Kasimu A, Fang C, Reheman R, Zhang X, Han F, Zhao Y, Aizizi Y, 2023. Establishing and optimizing the ecological security pattern of the urban agglomeration in arid regions of China[J]. Journal of Cleaner Production,427:139301.
[47] Xu L, Yang D, Wu T, Yi S, Fang Y, Xiao C, Lin H, Huang J, Habimana Simbi C, 2019. An ecosystem services zoning framework for the permafrost regions of China[J]. Advances in Climate Change Research,10(2):92-98.
[48] Brown G, Pullar D, Hausner V H, 2016. An empirical evaluation of spatial value transfer methods for identifying cultural ecosystem services[J]. Ecological Indicators,69:1-11.
[49] Wu S, Li S, 2019. Ecosystem service relationships: Formation and recommended approaches from a systematic review[J]. Ecological Indicators,99:1-11.
[50] Harwood A R, Lovett A A, Turner J A, 2015. Customising virtual globe tours to enhance community awareness of local landscape benefits[J]. Landscape and Urban Planning,142:106-119.
[51] Xu A, Hu M, Shi J, Bai Q, Li X, 2024. Construction and optimization of ecological network in inland river basin based on circuit theory, complex network and ecological sensitivity: A case study of Gansu section of Heihe River Basin[J]. Ecological Modelling,488:110578.
[52] Urbina-Cardona N, Cardona V O, Cuellar S, 2023. Uncovering thematic biases in ecosystem services mapping: Knowledge shortfalls and challenges for use in conservation[J]. Biological Conservation,283:110086.
[53] Gao C, Pan H, Wang M, Zhang T, He Y, Cheng J, Yao C, 2023. Identifying priority areas for ecological conservation and restoration based on circuit theory and dynamic weighted complex network: A case study of the Sichuan Basin[J]. Ecological Indicators,155:111064.
[54] Duan X, Zou H, Wang L, Chen W, Min M, 2021. Assessing ecological sensitivity and economic potentials and regulation zoning of the riverfront development along the Yangtze River, China[J]. Journal of Cleaner Production,291:125963.
[55] Walsh J R, Carpenter S R, Vander Z M, 2016. Invasive species triggers a massive loss of ecosystem services through a trophic cascade[J]. Proc Natl Acad Sci U S A,113(15):4081-4085.
[56] Li L, Feng R, Hou G, Xi J, Gao P, Jiang X, 2024. Integrating tourism supply-demand and environmental sensitivity into the tourism network identification of ecological functional zone[J]. Ecological Indicators,158:111505.
[57] Li C, Wu Y, Gao B, Zheng K, Wu Y, Wang M, 2023. Construction of ecological security pattern of national ecological barriers for ecosystem health maintenance[J]. Ecological Indicators,146:109801.
[58] Xu Z, Lin Y, Cai H, Zhang W, Shi J, Situ L, 2024. Risk assessment and categorization of terrorist attacks based on the Global Terrorism Database from 1970 to 2020[J]. Humanities

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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