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Realization of Integrated Regional Ecological Management Based on Ecosystem Service Supply and Demand Flow Networks: An Example from a Dominant Mineral Resources Development Area

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Abstract: Understanding the flow processes and pattern optimization of ecosystem services (ESs) supply and demand is crucial for integrated regional ecological management. However, the understanding of the flow process of ESs at the 1 km grid scale is still limited, especially in areas dominated by mineral resource development. The landscape in these areas has undergone significant changes due to mining activities. It is urgent to construct a regional management model that integrates the flow of ecosystem services and mine restoration. This study developed a framework that links ecosystem service flows (ESFs) and ecological security patterns (ESP) based on multi-source ecological monitoring data, constructed an ES supply-demand flow network through the flow properties, and determined the sequence and optimization strategies for mine rehabilitation to achieve integrated regional management. The results show that, except for food production (FP), other services were in surplus overall, mostly in synergistic relationships, but the spatial distribution of their supply and demand was not coordinated. Surplus areas were located mainly in the eastern woodlands, and deficit areas were located in the northwestern production agglomeration centers, suggesting that areas of supply-demand imbalance can be mitigated through ecological integration. Among these, water yield (WY) had a small number of sources and sinks and is limited in area range. Habitat quality (HQ) sources and sinks had the largest area coverage and the highest number. The distribution of ESF corridors, influenced by factors such as the number of sources and sinks, flow characteristics, and spatial resistance, varied significantly. HQ exhibited a more uniform distribution range, while WY had a longer average length of flow path. Overlaying ecological and mining factors, we identified ecological strategic spots, important supply areas, beneficiary areas, and mine priority restoration areas to further optimize the overall layout and rationally allocate the intrinsic structure of the patches based on ES supply and demand.

Keywords: integrated ecological management; ecosystem service flow; supply–demand; ecological security pattern; mine restoration

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1. Introduction

Against the backdrop of global climate change and accelerated urbanization, the sharp decrease in the area and increasing fragmentation of forests have directly affected the level of supply and demand of ESs [1,2]. The mining area is a complex geographic region. Long-term mining activities greatly change the structure and size of the forests, weaken the supply capacity of ESs, and increase the demand for many ecological services, such as food, water, and the environment, which are required for production [3]. The close

link between mining activities and the ES directly or indirectly constrains the region's sustainable development [4].

Over the past decades, there has been a gradual imbalance between the supply and demand of ESs, which has been slowly observed in many regions, such as the Yellow River Basin [5], Italian cities [6], the Barcelona metropolitan region in Spain [7] and the Basque Country [8]. This growing imbalance between the supply and demand of ESs has become a key influence on ecosystem management decisions, restoration planning, and compensation schemes [9–11]. Relevant studies have focused on quantification, equilibrium, and spatio-temporal characterization of the ESs supply and demand. Among them, scholars mostly assessed the ES supply and demand through scenario simulation, ecological value measurement, expert evaluation matrix, and ecological process modeling [12–14]. Considering the spatial differences in the ES supply and the exchange of material and energy flows in the ecological environment, the ecological sustainability of a region may depend on the ES supply capacity of other regions [15–17]. However, due to a limited understanding of ES supply-demand flows, how to adjust the landscape pattern to realize the balance of supply-demand and sustainable flow of ESs has become a research hotspot in the field of landscape ecology and regional planning [18–20].

The ES supply-demand flow refers to the spatial transfer between ES surplus and deficit areas, transferring excess services from SPA (service-providing areas) to SBA (service-benefiting areas). The spatial location largely determines the direction and efficiency of ESF, while the magnitude of resistance encountered during the flow process influences the specific path, aligning with the functional utility of ESP [21]. An in-depth exploration of the ESF characteristics can guide the allocation of landscape elements and optimize the delineation of ESP [22]. To this end, the source-sink theory is introduced to link the SPA, SBA, and spatial flow of ES with the ESP. It can effectively simulate the spatial paths of service flows, identify ES surplus and deficit areas, and optimize the landscape configuration by balancing the relationship between socioeconomic development and ecological protection [23,24]. Existing ESP studies usually construct different ecological network models based on the different roles of ES in sources, corridors, and other elements, different monitoring tools, and data accuracy [25,26]. Although most studies have considered multiple types of ESs, their ecological processes and flow characteristics are often ignored in the construction of resistance surfaces [27,28]. Individual scholars have combined ESP and ESF characteristics to construct the ES supply-demand flow network, which provides a reference basis for ES management. However, they mainly focus on the flow characteristics of a single specific ecosystem service [29] or analyze multiple ES supply-demand characteristics and flow directions using townships or even counties as research units [30,31]. Most current research focuses on watersheds, urban agglomerations, and even constituents but less on the flow characteristics of ES supply and demand in mining-dominated areas. It also fails to consider the impacts of mining activities on ES, as well as the integration of ESF and mine rehabilitation to achieve integrated regional management. In addition, existing research is often large in scale, ignoring the functional differences within the intrinsic configuration of landscapes. They tend to abstract sources, corridors, and ecological nodes as points or lines simply, lacking a finer research scale to achieve small patches' optimization [27,32].

The Mineral Resources Development Dominant Area (MRDDA) includes resource-based cities in Anshan, Fushun, Benxi, and Dandong, covering the area of the Liaoning Mine Ecological Restoration Project. The main mining type is coal, and frequent mining activities in the study area have led to a continuous deterioration in the overall quantity and quality of ESs, primarily manifested in geological safety hazards and landscape fragmentation. Geological safety hazards mainly include serious land deformation phenomena such as surface subsidence and ground cracks, which can intensify land use conflicts and change the type of regional ecosystems, with significant impacts on their ecological processes, functions, and structures [33]. Landscape fragmentation will threaten the supply and transmission capacity of ESs, directly affecting the direction and rate of ESF. It can be seen that mining activities have a major impact on the supply and demand of ESs selected in this

study (food production, water production, carbon storage, soil conservation, and habitat quality). It is necessary to integrate the characteristics of ESF with mine rehabilitation to achieve effective regional management [34]. Additionally, because the mines in the research region are many and small, the internal layout of various landscapes needs to be considered on a 1 km grid to accomplish optimization.

Therefore, this paper takes MRDDA as the study area, identifies the supply and demand characteristics of ESs from the 1 km grid scale based on multi-source ecological monitoring data and spatial analysis techniques, and constructs a framework for the integrated management of mine restoration and ESF features. The specific objectives are as follows: (1) evaluating the matching of ES supply and demand and the trade-off relationship; (2) identifying the analysis unit for ecological integration to determine the sources and sinks; (3) combining mine impacts and ESF features to construct resistance surfaces and ES supply-demand networks; and (4) delineating critical areas and proposing optimization strategies.

2. Materials and Methods

2.1. Study Area

Liaoning Province is located in the southern part of the northeastern region, bordering the Bohai Sea and the Yellow Sea (38°43′–43°26′N, 118°53′–125°46′E). The terrain is high in the north and low in the south. The total area is 148,600 km^2, which is about 1.5 percent of the total area of the country. The Mineral Resources Development Dominant Area (MRDDA), with an area of 35,791.91 km^2, is located in the eastern part of Liaoning Province and is an area where mineral resources development is the predominant form of development (Figure 1). Forests and grasslands, which account for more than 78 percent of the total area, dominate the landscape, and the terrain is high in the center and low in the surrounding areas. At the same time, the region is relatively rich in mineral resources, with coal, iron, and granite mining dominating. The large number of open-pit mines has led to fragmented topography and land degradation, resulting in regional land subsidence and mining-related safety hazards such as cracks, avalanches, and landslides, which seriously affect the supply and stability of the region's ESs [35].

2.2. Materials and Data Proceeding

The data used in this study were mainly collected and processed by the GEE platform and ArcGIS, and the resolution is unified by the resampling tool. Since most of the data collection accuracy is 1 km, the resolution of the data in this study is unified to 1 km. The Climate data are generated based on the National Weather Station dataset (2000) using Anuspl (Version 4.4) software interpolation (Table 1).

Table 1. The detailed descriptions and data source.

Data	Description	Resolution	Source
LUCC	Being classified into 6 types	30 m	Landsat-5,7,8 (https://earthengine.google.com/)
Climate data	Data about precipitation, temperature, evapotranspiration	Weather station	Chinese meteorological data network (http://data.cma.cn/)
Soil data	Data about sand, silt, and clay content (%), soil depth, organic carbon (%)	1 km	Harmonized World Soil Database (HWSD) (http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/).
DEM	Data about elevation and slope	30 m	Geospatial Data Cloud (http://www.gscloud.cn)
Population	Population density (person/km^2)	1 km	National Qinghai-Tibet Plateau Scientific Data Center
GDP	Gross domestic product density (1 × 104 yuan/km^2)	1 km	
Nighttime light data	The Light Information of Earth at Night	1 km	NPP/VIIRS dataset (https://www.ngdc.noaa.gov/eog/viirs/download_dnb_composites.html)

Table 1. *Cont.*

Data	Description	Resolution	Source
Geologic environment	Geological disaster risks and Location of the mines in the study area		Natural Resources Agency of Liaoning Province
Vector map data	Administrative divisions in China		National Geographic Information Resource Catalog Service System (https://www.webmap.cn/)
Statistical data	Data about crop yield, energy consumption, and water consumption		Water Resources Bulletin; The Liaoning Provincial Bureau of Statistics

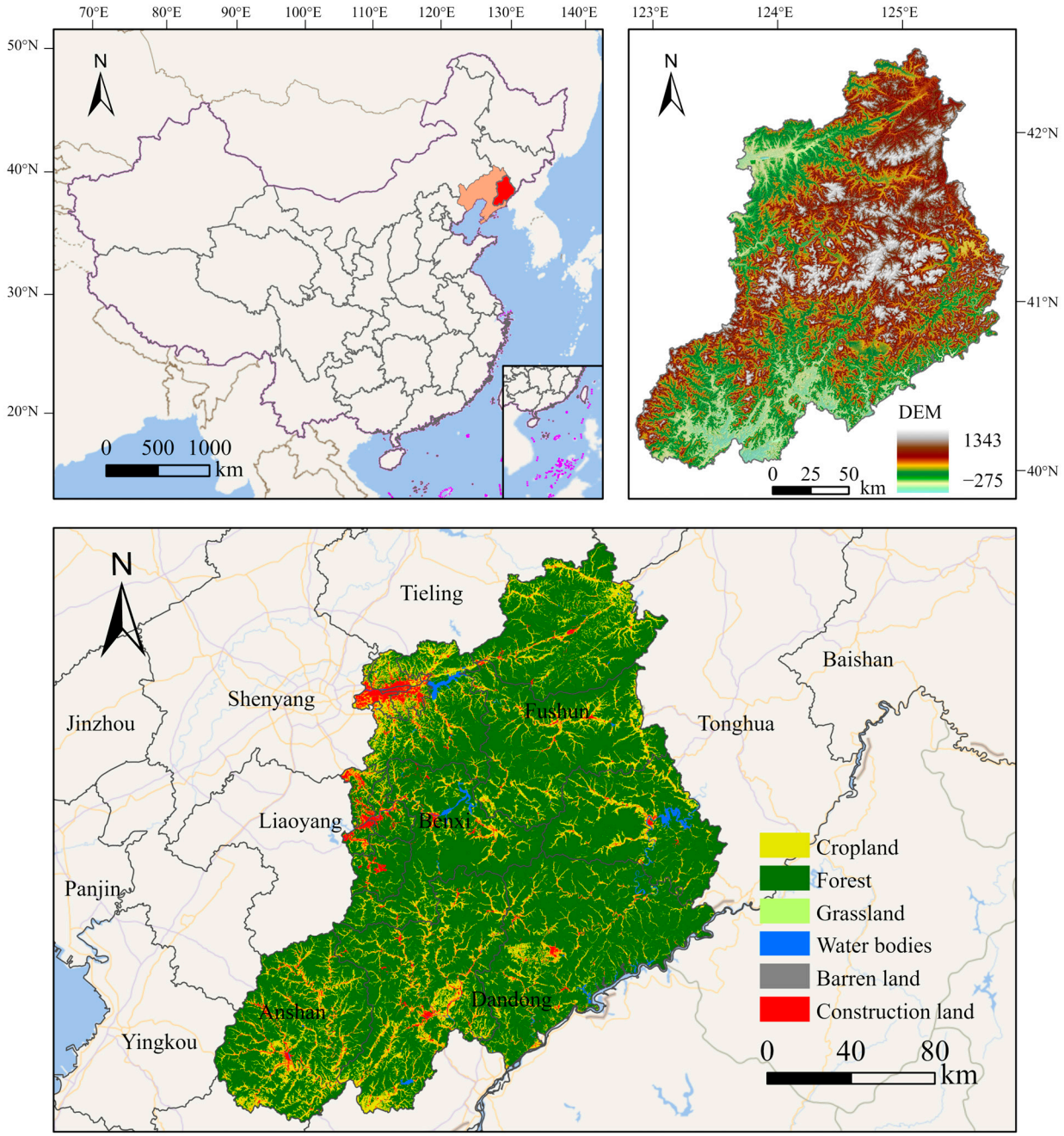


Figure 1. An overview map of the MRDDA.

2.3. Analytical Framework

We quantify the supply and demand of FP, SC, WY, CS, and HQ through InVEST, link ESF characteristics with ecological networks to construct an ES supply-demand flow network and identify key areas for network optimization to provide planning strategies for regional integration management (Figure 2).

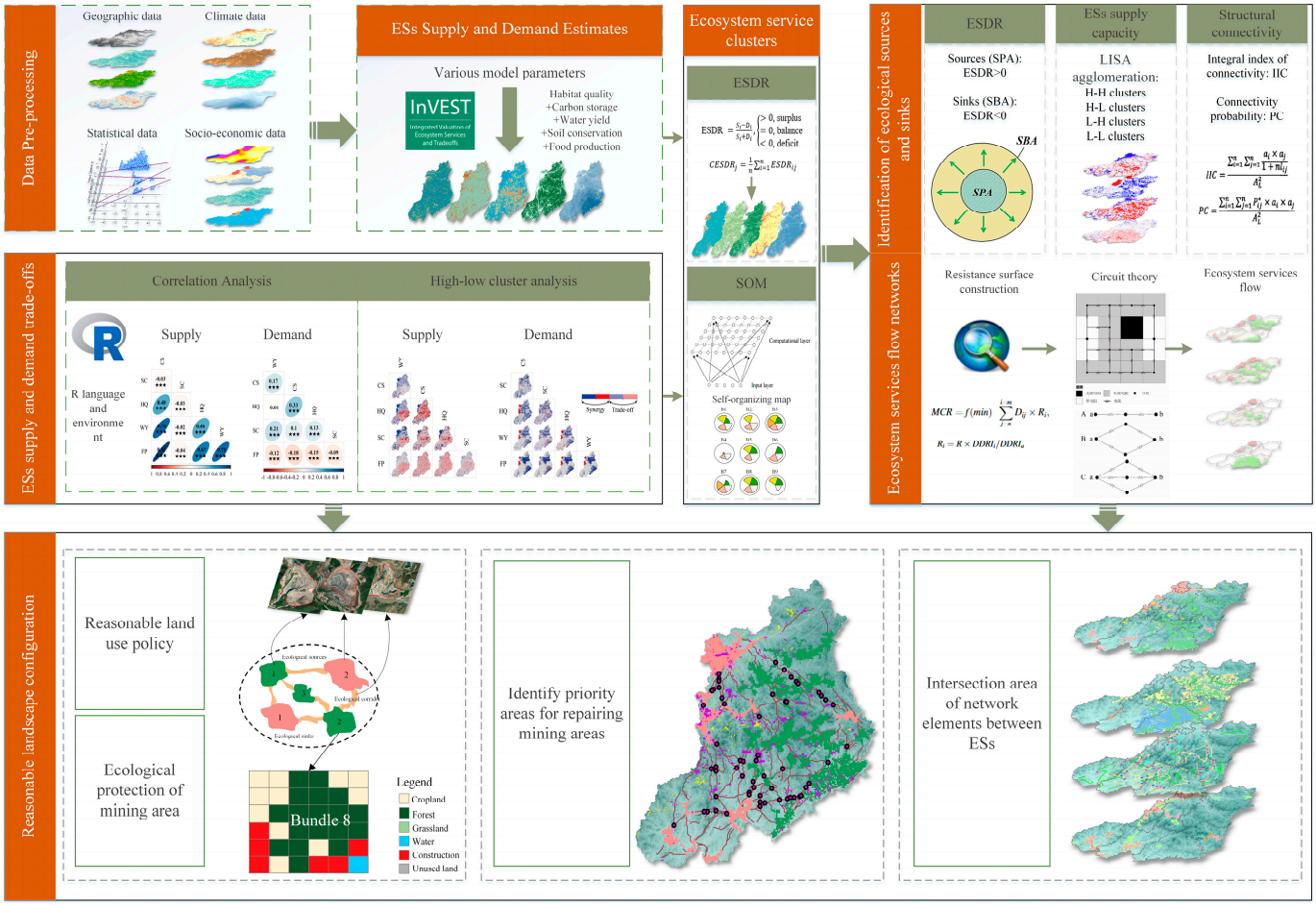


Figure 2. Framework to delineate ES supply and demand flow network.

2.3.1. ESs Supply-Demand Matching and Trade-Off Analysis

The selection of ES for this study is based on three criteria: (i) Classification framework based on the Common International Classification of Ecosystem Services (CICES), i.e., provisioning services, regulating services, and cultural services. (ii) Development objectives: The ecological protection plan proposed to actively improve the soil environment in mines, restore wetland habitat conditions, and comprehensively improve the quality and stability of the ecosystem. (iii) Practical needs: Frequent mining has caused landscape fragmentation, soil erosion, and ground subsidence, seriously threatening the cyclic flow of material, energy, and information in the region. Five main services are selected based on the above criteria: FP, WY, CS, SC, and HQ (Table 2). We assess the supply and demand of the above services on the 1 km grid scale [36]. Specific information on ES supply and demand assessments is provided in the Supplementary Material.

Table 2. Overview of ESs supply and demand assessments.

ESs	Type	Methods	Description
FP	Supply	Measurable NPP equation	The food supply capacity of agro-ecosystems [37].
	Demand	Estimated based on per capita food demand standards and population size	Socio-ecological system food demand
CS	Supply	The CS module of the InVEST 3.10.0	Carbon storage capacity of terrestrial systems [38].
	Demand	Quantified by the consumption and carbon emission coefficient of standard coal	Carbon emissions from industries, services, and households [39].
WY	Supply	The WY module of the InVEST 3.10.0	The water production capacity of the ecosystem [40].
	Demand	Urban Water Balance Sheet	Water consumption for agricultural, industrial, domestic, and ecological environment [41].
SC	Supply	RUSLE model	The difference between the potential soil erosion and the actual soil loss [42].
	Demand	A threshold for soil retention management	The necessity of soil erosion prevention [16].
HQ	Supply	The HQ module of the InVEST 3.10.0	Ecosystems provide a quality of environment suitable for living organisms.
	Demand	Spatial analysis tools of ArcGIS 10.6	The level of environment required for the survival of organisms [43].

ESs Supply-Demand Ratio

ES supply-demand ratios (*ESDR*) can reveal deficit or surplus characteristics in different regions [44]. The composite supply-demand ratio (*CESDR*) of ESs can be used to demonstrate the overall state of multiple *ESDRs*, as expressed through the arithmetic mean of the supply-demand ratios of five selected ESs [45].

$$\mathrm{ESDR} = \frac{S_i - D_i}{S_i + D_i}, \begin{cases} > 0, \text{ surplus} \\ = 0, \text{ balance} \\ < 0, \text{ deficit} \end{cases} \quad (1)$$

$$CESDR_j = \frac{1}{n} \sum_{i=1}^{n} ESDR_{ij} \quad (2)$$

where S_i is the ES supply for grid i and D_i is the ES demand for grid i. $ESDR > 0$ indicates that the supply is higher than the demand, $ESDR < 0$ indicates that the supply is less than the demand, and $ESDR = 0$ indicates that the supply and demand are in equilibrium; $CESDR_j$ is the $CESDR$ in grid j, n is the number of ES types, and $ESDR_{ij}$ is the ratio of supply and demand for type i in grid j.

ESs Trade-Offs and Synergies

In this study, the Pearson correlation coefficient and LISA agglomeration analysis are used to explore the synergies and the trade-offs between the supply side and demand side of ESs. The Pearson correlation coefficient is used to analyze the trade-off relationship between the ES values, while the LISA agglomeration reveals the spatial distribution of ES trade-offs.

2.3.2. ESs Supply and Demand Flow Network Framework

Identification of ESDRs Bundles

The self-organizing mapping method (SOM), as an efficient algorithm for cluster analysis, identifies ESDR bundles by spatial clustering of grids. These grids have similar characteristics among ESDRs, which can provide a reference for the formulation of spatial management measures [46,47]. Different numbers of clusters (from 2 to 20) were constructed to explore the sensitivity of the self-organizing mapping results, and then the Davies-

Bouldin value was calculated to determine the optimal number of clusters within the study area as 9. See Supplementary Material for specific information.

Delineation of Source and Sink

In this study, the terms "sources" and "sinks" are defined as areas of service surplus and areas of supply deficit, respectively. To accurately identify the sources and sinks, the screening process is based on an analysis of the function and structure of ESs. Firstly, the supply and demand characteristics of ESs are evaluated based on BESDRS, and areas with robust service supply capacity are identified. Secondly, high-high agglomeration types are screened based on LISA agglomeration, and grids exhibiting a dispersed spatial pattern are excluded. Finally, in consideration of the attributes of its network structure, areas with dPC values exceeding 0.01, indicative of a source, were identified through Conefor2.6 [48,49]. This approach ensures that the identified sources possess a robust service supply capacity and exhibit a high degree of concentration. In addition, since sinks are under-supplied areas, the screening criteria for BESDRS and agglomeration type are opposite to those used for sources. Finally, the area threshold for source and sink patches was set at 30 km^2 based on the number and size of patches identified in related studies [50].

Construction of Resistance Surface Based on ESF Features

The flow of ES is subject to transmission resistance from the supply area to the beneficiary area, and different service flows present different transmission modes. There are three primary diffusion modes: natural (CS and HQ), semi-natural (WY and SC), and artificial (FP) [16]. The carriers of ESF and spatial resistances vary, and relevant studies can be referenced to identify the main influencing factors and resistance values for service flows such as WY, CS, SC, and HQ (Table 3).

Table 3. The resistance values for ESF.

Type	HQ	Weight	WY	Weight	CS	Weight	SC	Weight
LUCC	√	0.4055	√	0.2348	√	0.3025		
Slope	√	0.2374					√	0.2757
Elevation			√	0.1954			√	0.2853
NDVI	√	0.202			√	0.2824	√	0.258
Recessive resistance	√	0.1551			√	0.1997	√	0.1811
Stream order			√	0.3075				
Water demand			√	0.2624				
Wind speed					√	0.2154		
Correction factor	√		√		√		√	

Finally, to take into account the significant influence of anthropogenic activities on the ESF, the geohazard risk and night lighting data were selected to correct the resistance surface [51]. In the process of categorization of resistance factors, the categories are classified by the natural breakpoint method to ensure the difference in resistance coefficients, and the weights of resistance factors are calculated through AHP.

$$Ri = R \times DDIi/DDIn \quad (3)$$

$$DDIi = 0.5 \times GRI + 0.5 \times ELIGHT \quad (4)$$

where Ri is the resistance value of grid i, R is the initial resistance surface, $DDIn$ is the total value of the disaster disturbance risk index, and $DDIi$, $GRIi$, and $ELIGHT$ denote the disaster disturbance risk, geohazard risk, and nighttime lighting index of grid i, respectively. Geohazard risk was obtained by spatial interpolation of geohazard hazard frequencies and normalized to calculate DDI.

Identification and Optimization of ESs Supply-Demand Flow Network

Existing studies often quantify biological flow paths in space through circuit theory, highlighting active and communication-barrier regions for species movement [52]. So, this study used the Link Mapper tool, which integrates the MCR model and the circuit theory, to extract corridors and nodes and depict corridor extent [28].

Due to the multifunctionality of the landscape, different service flow paths intersect with each other, resulting in severe redundancy in the ES supply-demand flow network and a cumulative increase in flow resistance. The corridor level is classified by the flow magnitude of the source, and the redundancy degree of the network is combined to eliminate the corridors with overlapping distribution and low utility and add stepping-stones to optimize the ES supply-demand flow network.

2.3.3. Delineation of Key Areas and Strategic Points

Identification of Key Areas

To identify critical areas in the flow network, we overlay the supply and demand networks of HQ, CS, SC, and WY. Sources and sinks are important areas in the network analysis, determining the study objectives and corridor direction, and each source and sink represents the key supply and deficit areas of ES. Therefore, we use the overlap areas of ES sources and sinks as the key areas in the flow network, which can effectively identify key supply and deficit areas of regional ESs. Critical areas in mine rehabilitation refer to mines in key positions in the ESs flow network, which seriously affect the efficiency of ESFs. Therefore, we consider the mines along the corridor pathway, the mines inside the sources and sinks, and the mines around the strategic points as the critical areas for restoration, which need to be prioritized for restoration and control.

Identification of Strategic Points

Due to the topological characteristics of networks, intersection points are usually the more vulnerable areas in the network structure. ES flow paths act as spatial corridors for material and energy flows, and the intersection points between corridors are the most sensitive areas in the flow process of ESs, which we define as strategic points. These points represent key hubs for two or more ESs, which largely determine the flow efficiency. However, they are also fragile and vulnerable, which makes it important to identify and protect them [53].

3. Results

3.1. ESs Supply-Demand Matching and Trade-Offs

3.1.1. Assessments of ES Supply and Demand

This study analyses the spatial features of ES supply and demand, such as HQ, CS, SC, WY, and FP in 2020 (Figure 3). As far as the supply of ESs is concerned, its spatial distribution is not uniform and varies significantly. The spatial pattern of CS, WY, and HQ supply is relatively similar, generally showing a distribution pattern of low in the northwest and high in the southeast. The low-value zones are consistently distributed, located in the population agglomeration centers in the northwestern part of the study area and spreading along major transportation roads. The high-value zones are mainly located in the central and eastern parts of the study area, with high vegetation cover, which is one of the important ecological barriers. The high-value areas of WY supply are distributed in the southeast, influenced by climatic precipitation. The spatial pattern of FP is roughly opposite to that of other services. Most of the high-value areas are at lower elevations, coinciding with the SC supply low-value areas, and are scattered around population concentration areas. The SC exhibit a pattern of higher values in the center and lower values in the periphery. The central area features dense vegetation and higher elevation, while the surrounding regions characterized by frequent human activity show lower values, which is consistent with the actual situation.

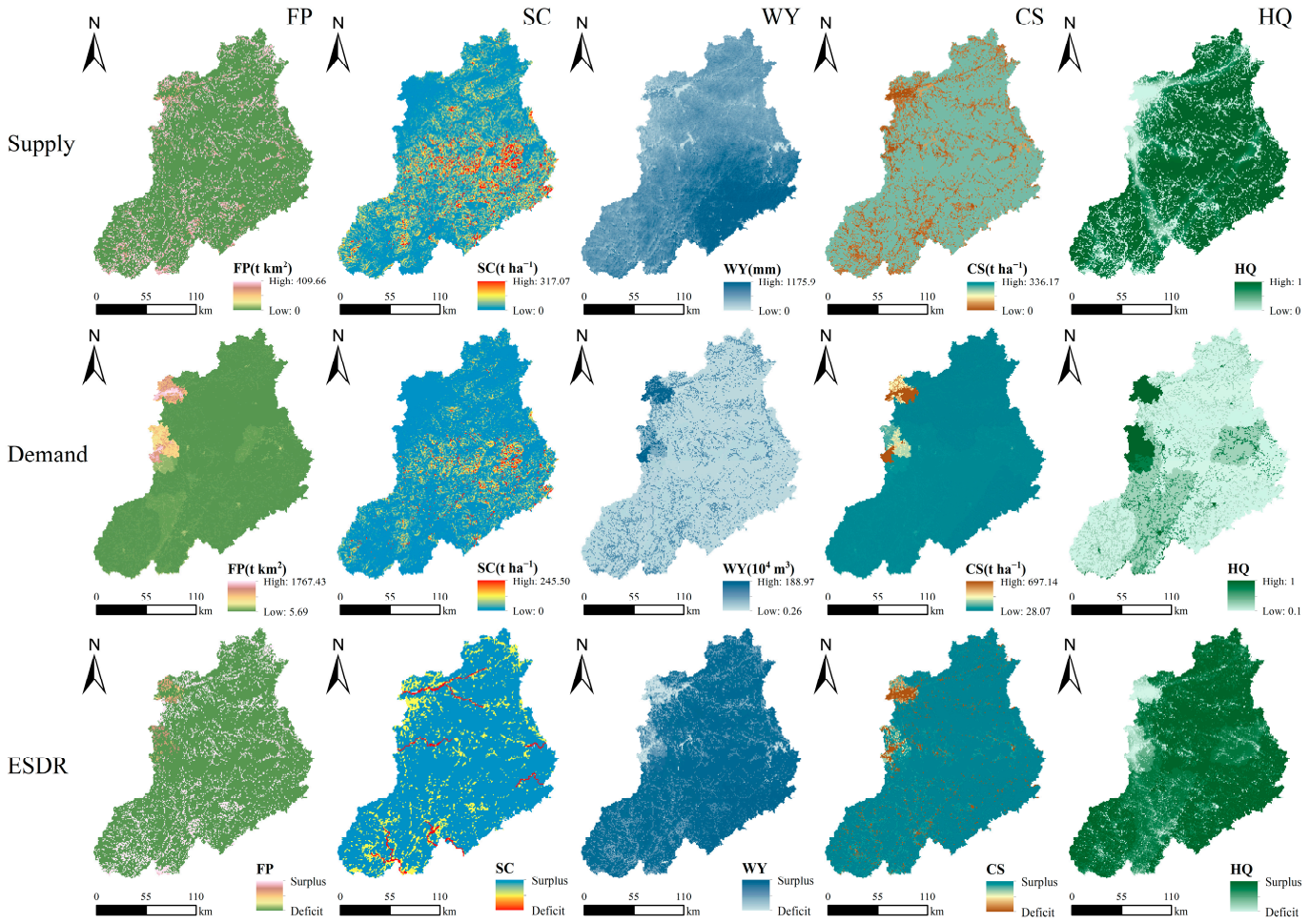


Figure 3. Spatial distribution of ESs supply and demand matching.

In terms of the spatial pattern of ES demand, the distribution characteristics of FP, CS, HQ, and WY are similar. The high values are concentrated in the northwestern where population and industry are concentrated, closely linked to the distribution of construction land. This reflects the great demand for natural ecosystem services from human activities. Other areas of woodland, grassland, and other land types have lower values of demand. The demand and supply patterns in SC are similar, but the range of high-demand values is much smaller than the high-supply areas. It is strongly influenced by the elevation and landform type of the study area.

The spatial pattern of ES supply and demand matching varies, with significant spatial heterogeneity. HQ, SC, CS, and WY as a whole are all in oversupply, with the range of supply surpluses much larger than the deficit areas. The deficit areas for these services coincide with their high-value areas of demand and are mainly located in the north-west where there is more human disturbance. The surplus areas are in line with the high-value areas of service supply. FP is in a state of under-supply, with more deficit areas. This is mainly due to the small extent of cropland in the study area, which is scattered among other land types. The surplus areas of FP are mainly located in human agglomerations, which is in line with the flow characteristics of FP. In general, most of the surplus areas of ESs are concentrated in the central and eastern vegetated areas, while the service deficit areas are in the northwestern population centers. It can be seen that the supply and demand status of ES is mainly influenced by natural resource endowment and social activities. For example, the surplus areas of FP are centered on population centers and distributed along major transport routes.

3.1.2. ESs Supply-Demand Trade-Offs

The values of ES supply and demand show that there are significant trade-offs between both the supply side and the demand side, with varying strengths (Figure 4). In terms of the supply side of ESs, FP is in a trade-off relationship with all other ESs, with the strongest trade-off with SC (r = −0.18). SC was a significant synergistic promoter with all other ESs, with a stronger role with WY (r = 0.21). The interaction between CS and WY, HQ was synergistic, with the highest intensity of interaction between CS and HQ (r = 0.33). The relationship between the demand side of ESs was characterized clearly, with a trade-off between SC and all other ESs, which is weak (r < −0.05). In contrast, FP, WY, CS, and HQ are all synergistic with each other, with CS having the strongest synergistic effect with FP and WY at 0.92 and 0.75, respectively.

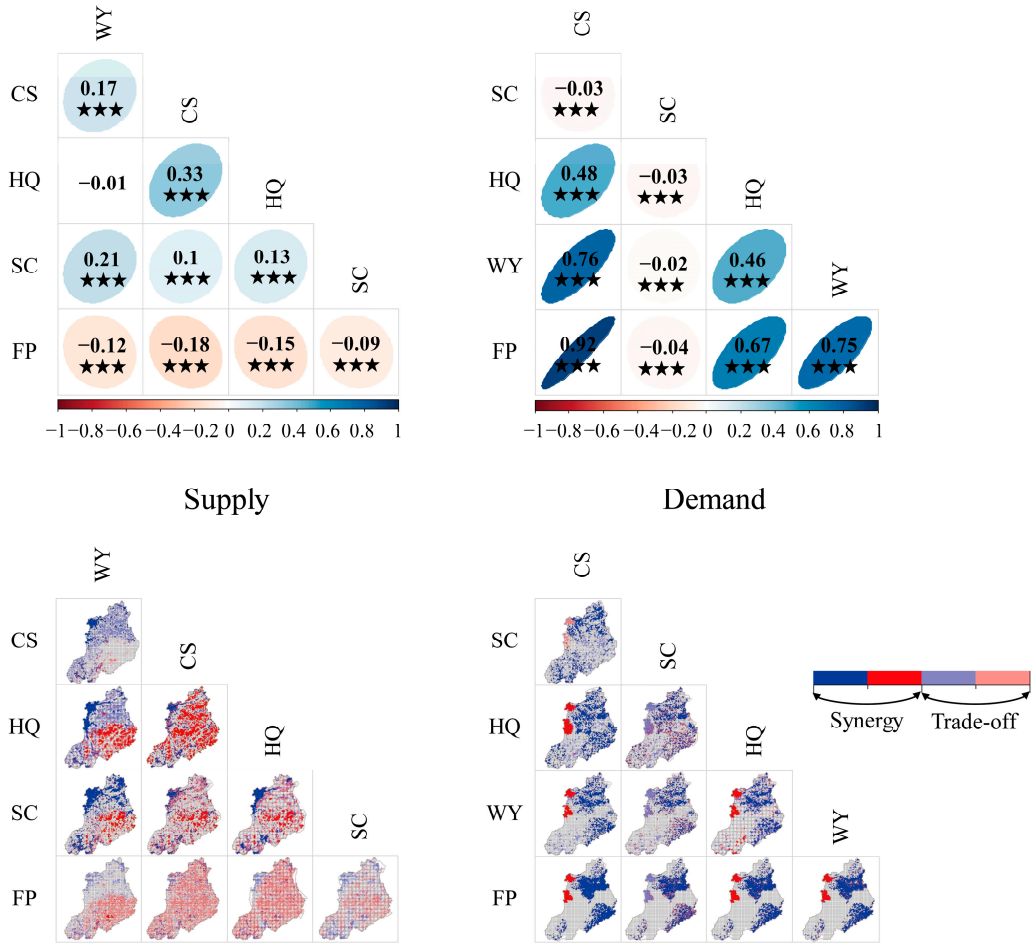


Figure 4. The trade-off between ESs supply and demand. Notes: Significance test results. ★ $p < 0.10$; ★★ $p < 0.05$; ★★★ $p < 0.01$.

In general, the interactions on the ESs supply side are largely synergistic, while FP and other ESs are trade-offs with similar strengths. On the ESs demand side, except for SC, there are significant synergistic relationships among ESs, and the synergistic effect is significantly stronger than the trade-off effect. This indicates that the FP supply capacity slowly diminishes as the supply capacity of services such as HQ, CS, and WY gradually increases, which is closely related to the landscape structure. The trade-off relationship on the ESs demand side, on the other hand, reflects the consistent human demand for freshwater, energy, food, and ecosystems. SC demand is continuously reduced by the impact of human construction.

In terms of the spatial distribution of supply and demand relationships, the spatial distribution of the supply side and the demand side varies greatly in scope. As far as the

supply side is concerned, the trade-off types between FP and other ESs are mainly located in the center and east, with the widest range of trade-offs with CS, accounting for 40.27% of the total area. The synergy types on the supply side of other ESs are mainly located in the northwest and the center, with HQ having the widest synergy with CS, accounting for 36.2% of the area. Among the demand sides, SC has a similar spatial trade-off layout with other ESs, mainly distributed in the northwest with a smaller range. The synergy types between the demand sides of other ESs are distributed in the north and southeast of the study area, with highly consistent spatial distribution. Among them, the CS and FP synergies have the largest range, with an area share of 29.74%.

3.2. Construction of ES Supply-Demand Flow Network

3.2.1. Cluster Analysis of ESDRs

The spatial distribution of BESDRS is heterogeneous and closely related to the landscape types, mainly in the structural differences among the four landscapes: cropland, woodland, watersheds, and built-up land, which give rise to different ES supply capacities (Figure 5). Clusters 2, 7, 9, 6, and 8 have a similar land-type composition, showing a trend of shrinking woodland and expanding cropland and building land. The match between supply and demand for services such as HQ and WY is constantly weakening, with BESDRS 9 having the highest average level of supply. It has significant multiple ES surpluses and overall shows ES supply hotspots. BESDRS 2 has the next highest level of supply and the widest distribution and is the baseline type of service function in the study area. The levels of supply and demand in clusters 3 and 5 are broadly similar, with the difference being in the level of WY supply and demand. While WY in BESDRS5 shows a strong supply surplus, there is a severe shortage of WY in BESDRS3, which is closely related to zonal precipitation. Clusters 1 and 4 have a large difference in landscape structure and ESDRs. Cluster 4 represents a key source of demand for ESs, and only WY is in a state of supply surplus. Compared to cluster 4, the surplus of services in cluster 1 is generally enhanced, mainly due to the gradual decrease of forestland and cropland and the significant increase of built-up land in cluster 4.

Overall, FP supply is limited and insufficient in total. Clusters 1 and 9 have multiple ES supply surpluses and can serve as ES supply hotspots. In contrast, there is cluster 4, where several services are under-supplied and in high demand. The supply and demand capacities of ESs in different clusters vary, so the clusters can be screened according to different research objects.

3.2.2. Identification of Sources and Sinks

The above analysis indicates that the FP supply capacity in the study area is limited while the demand is high, resulting in an overall supply shortfall that hinders the balance of food supply-demand flows. For this reason, this study intends to explore the supply-demand flow networks of CS, SC, HQ, and WY and to identify the sources, sinks, and spatial flow paths under different constraints.

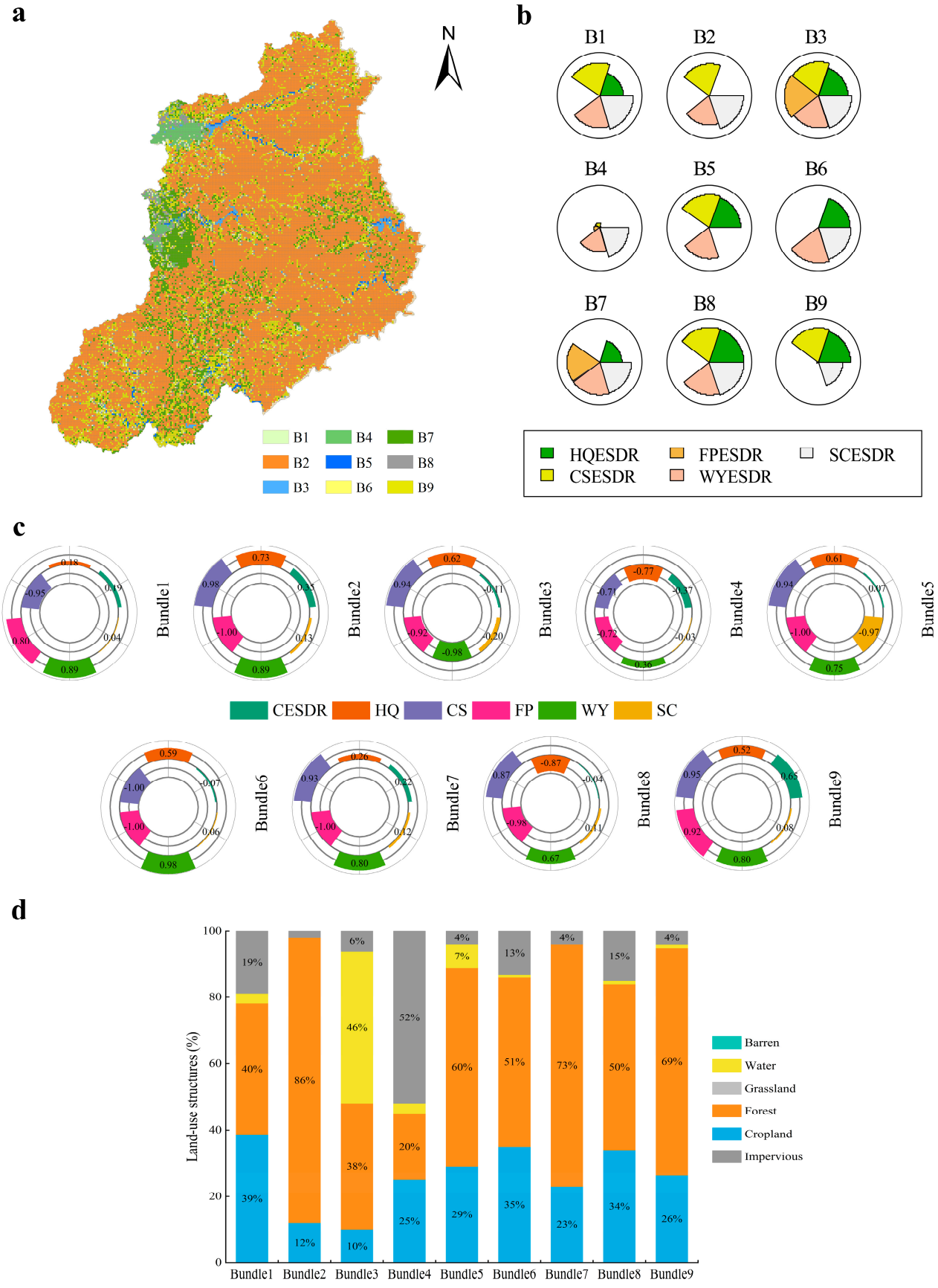


Figure 5. Bundles of ESDRs in MRDDA: (**a**) the spatial distribution of BESDRS; (**b**) the types of BESDRS; (**c**) the mean ESDR in BESDRS; (**d**) land-use structures in BESDRS.

Based on the service cluster categories and the spatial agglomeration characteristics of ESs, patches with surplus and agglomeration type H-H were selected as the source of ES supply-demand networks to guarantee the sustainability and supply capacity of ESs. Sinks then identifies patches by ESDR < 0, filtering out the range of specific ES in short supply. The total number of CS, HQ, SC, and WY sources are 8, 10, 10, and 5, respectively, with area shares of 14.32, 15.11, 5.67, and 16.97 percent, respectively. The total number of sinks is 8, 10, 8, and 5, with an area share of 6.65, 10.58, 4.86, and 3.6 percent, respectively. The spatial distribution of sources and sinks varied (Figure 6), with the sinks being more consistently located in the northwestern and southern parts of the study area, i.e., in the population centers, and the landscape is dominated by built-up land. The spatial distribution of sources varies with the type of ES. CS sources are mainly located in the northern and southeastern vegetated areas. HQ sources are located in the central high-altitude area, which is less affected by human activities. SC sources are distributed similarly to HQ but with a limited range. WY sources are concentrated in the southeastern part of the study area, which is adjacent to the ocean and has abundant precipitation, and thus has a stronger supply capacity of WY.

3.2.3. Construction of Resistance Surfaces and ESs Flow Networks

Resistance surfaces for CS, HQ, SC, and WY supply-demand flows were constructed respectively based on the flow characteristics of ESs (Figure 6). The combined resistance surfaces of the four ES flows differed significantly, among which CS and HQ resistance surfaces had similar characteristics. The high resistance values are scattered in the built-up land in the northwest and southeast, mainly due to human activity interference. The low resistance values are widely distributed in the ecological land, such as woodland and grassland in the study area. The high values of SC resistance surface are scattered in the central and northern parts of the area with higher elevation, while the low values are mainly concentrated in the southern part of the study area, which is greatly influenced by the elevation and vegetation. The WY resistance surface pattern is different from other services, with high values concentrated in the arable and built-up land and low values widely distributed in the form of strips, roughly in line with the course of the rivers in the region.

We identify the flow paths based on circuit theory and then construct ES supply-demand flow networks by combining sources and sinks. The number of corridors for ESs is directly proportional to the number of sources and sinks. There are 44 flow paths between HQ sources and sinks, and the number of paths between WY sources and sinks is the lowest at 18. Combined with the source and sink hierarchy to classify the importance of flow paths, the results show that SC has the highest percentage of first-level corridors between sources and sinks (51.28%), and WY has the lowest percentage of first-level corridors (33.33%). Meanwhile, the SC corridor has the largest total length of 1225.306 km, and the longest and shortest corridors are 91.982 km and 1.414 km, respectively. The WY has a total length of 574.748 km, and the longest and shortest corridors are 128.367 km and 1.414 km, respectively. The distribution of the flow network shows that SC and WY flow in roughly the same direction, from the eastern source to the northwestern sink. The WY corridor is longer and traverses the central vegetated area and some secondary corridors in the SC flow to the south. HQ supply-demand flow paths are more evenly distributed, with flows covering the entire study area. The CS flow network forms a circle based on the main sources and sinks, with fewer north-south flow paths in the center, which is closely related to the distribution of high-resistance areas such as production land. Due to the poor natural conditions and the interference of human activities, it is necessary to safeguard the cyclic supply of ESs in the region by strengthening the protection of the adjacent areas of the corridor.

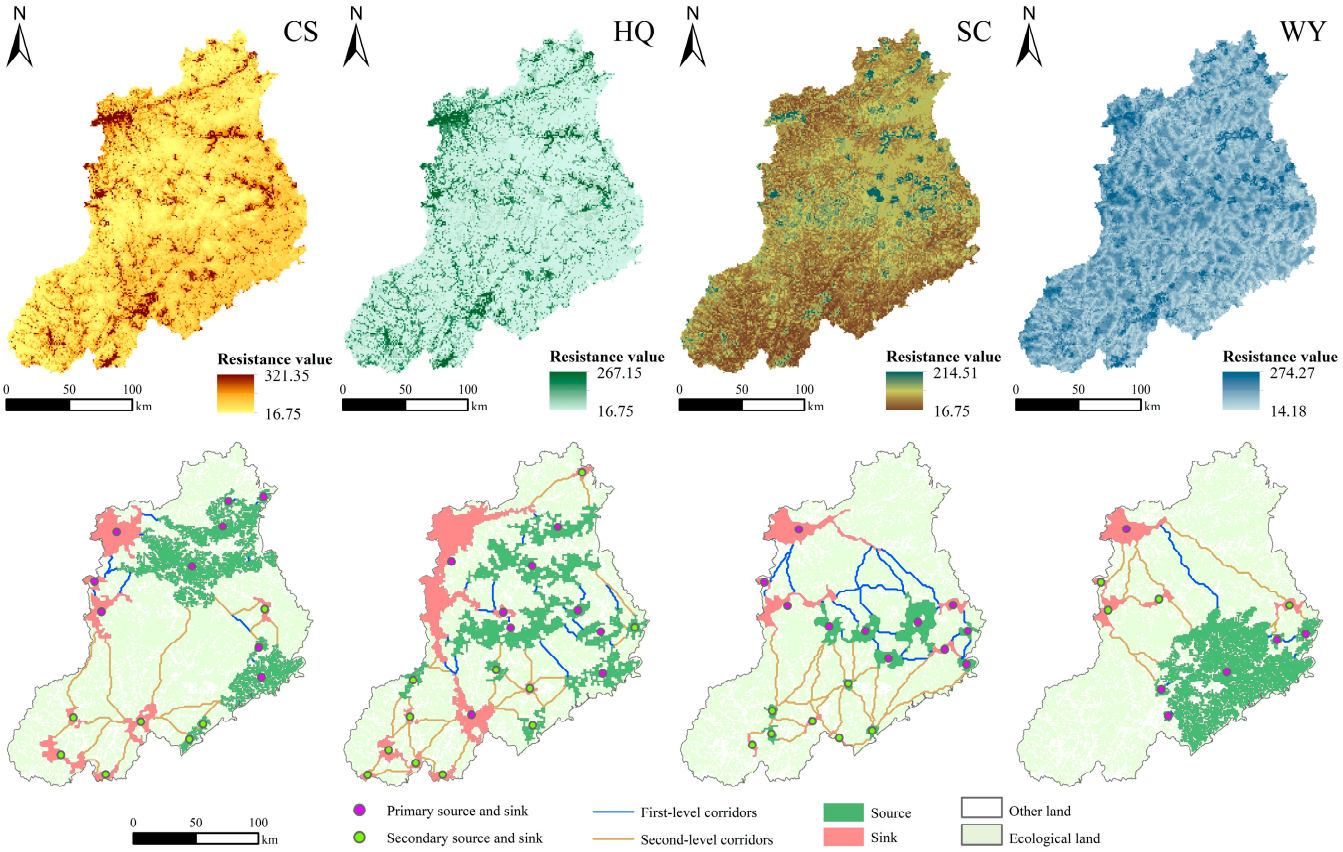


Figure 6. ESs supply-demand flow network.

3.3. Identification and Optimization of Critical Areas in ES Flow Networks

3.3.1. Identification of Critical Areas

Due to the multi-functionality of ESs in landscapes, the network elements constructed based on the ESF characteristics have certain spatial overlapping areas. It mainly includes critical areas between sources and sinks and ecological strategic points identified by the intersection between different service flow paths (Figure 7). The intersection of sources varied greatly among different ESs, with HQ and CS having the widest overlap of 2357.66 km^2, accounting for 43.59% and 45.99% of the HQ and CS source areas, respectively. These areas are mainly located in the eastern and northern woodlands. Other ES source overlap areas are concentrated in the eastern vegetation cover area of Dandong City, ranging in size from 145.25 km^2 to 1777.7 km^2. The overlapping areas of sinks are limited in scope and distinctive, concentrated in the western and southern parts of the study area. It corresponds to the main landscape types of construction land, cropland, and water bodies. Among them, the intersection area of HQ and CS is larger, which is 2068.57 km^2, accounting for 54.62% and 86.95% of the HQ and CS sinks, respectively. The overlap area of SC and WY is the second largest, and the area of HQ and WY is the smallest, with the area ranging from 656.78 km^2 to 1289.16 km^2.

To further identify key hubs in the ESs flow network, this study identified 60 ecological strategic points for ecological restoration and optimization by overlaying the flow corridors of four services, including HQ, CS, WY, and SC. Among them, there are 36 secondary corridor points and six primary corridor points. These strategic points seriously affect the flow of material and energy in the regional ecosystem and the linkage of different ecological services. In terms of its spatial distribution, the points of CS with SC and HQ corridors are distributed around the arable and built-up land in the south, and the points of WY with SC, HQ, and CS are located in the cropland and forest in the north. In general, the strategic points are divided by high-elevation vegetation areas in the central part and

show a north-south pattern. These points are mainly located close to cropland and built-up land, avoiding high-elevation vegetation zones. This is largely consistent with the range of human footprints, for which protection and planning key areas should be enhanced. At the same time, there are a certain number of open pit mines in the study area with serious safety hazards, blocked material, and energy channels, which constantly threaten the quality and sustainability of ESs. For this reason, we determined the rehabilitation sequence of existing mines based on the above key areas (Figure 7d). As can be seen from the figure, while the mines in the study area are limited in size, they are numerous and scattered, requiring substantial financial and human resources for uniform rehabilitation. Some of the mines are in spatial conflict with the elements of the ES flow network, among which the overlap with the sinks is more obvious, concentrated in the center of production activities. The rest of the conflict mines are located around the source and strategic points, corresponding to the landscape of construction land and woodland. At the same time, many mines conflict with ESs flow paths, which inevitably hinder or weaken the supply and flow efficiency of ESs. Mines that conflict with sources, impede the supply-demand flow, and are located in areas around strategic points are uniformly classified as priority restoration areas, while those that conflict with sinks are strengthened for controlled development (Figure 8a).

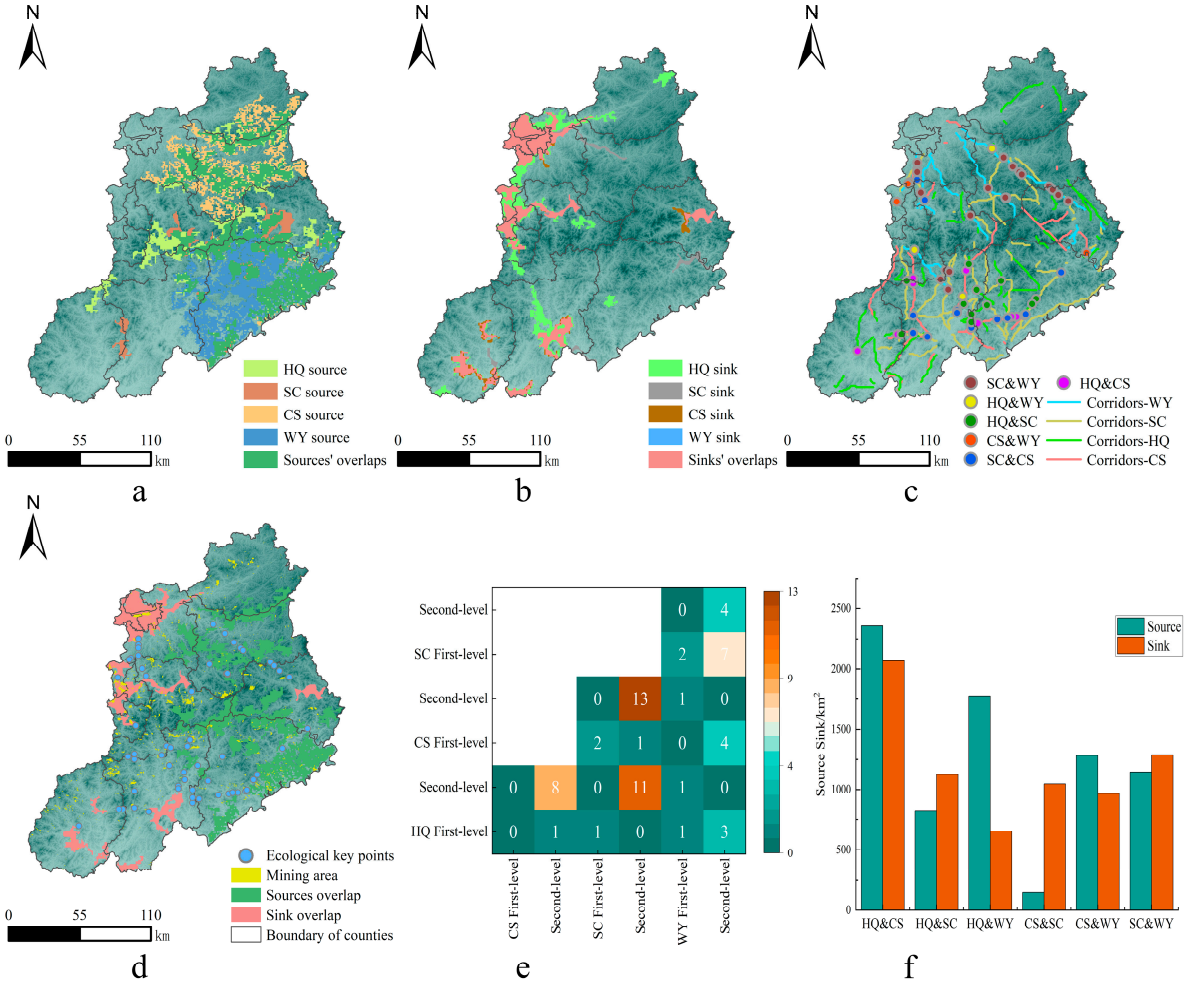


Figure 7. Delimitation of critical areas of the ESs flow network: (**a**–**c**) denote the spatial distribution of sources, sinks, and corridors of the ES, respectively; (**d**) denotes the spatial distribution of network element intersections; (**e**) denotes the number of corridors intersecting at different levels; and (**f**) denotes the area of the intersection of sources and sinks.

3.3.2. The Optimization of ES Flow Networks

Based on the construction of the flow network above, we obtained the flow pattern and key areas of ES supply and demand (Figure 8a). Combining the spatial characteristics of the sources, sinks, and corridors, three planned source areas are added as stepping stones to optimize the overall ES flow path in the region. It can be seen that the optimized network is mostly ES main corridors, the duplicate corridors are greatly reduced, and the flow network of regional circulation is constructed (Figure 8b). This study proposes a model of ecological protection and mine rehabilitation that integrates the ES flow based on landscape multi-functionality. The method forms a regional ESs supply-demand flow network by overlaying ecological elements of various services and integrating the key areas of ESs with mine rehabilitation, thus achieving a coordinated layout of mine disturbances and ESs supply-demand flows. Among them, the source and sink intersection areas are important protected areas and suitable development zones, respectively, and the planned source area is designated as a priority protected area. The corridors of the optimized network and their 120 m buffer zones are classified as important protected areas. Due to the different attributes and levels of the corridors, they are classified into four types: demand transition, functional enhancement, process prevention, and multi-functional complex, and the corresponding protection measures should also be different. Source-source process prevention corridors should aim to ensure ES supply capacity, and source-sink function improvement corridors should improve the efficiency of ES flows based on resistance surface factors. The demand transit of sinks-sinks should be based on the characteristics of ES demand to promote its transit flow, for example, carbon, food, and water flows in the process of socio-ecological initiatives have different effects. The strategic points are important protected areas that guarantee the ES flow efficiency. The open-pit mines around the above important protection zones are classified as priority restoration zones, while the rest of the mines are classified as suitable development zones and general restoration zones according to their attributes so that different types of zones will be subject to targeted optimization strategies.

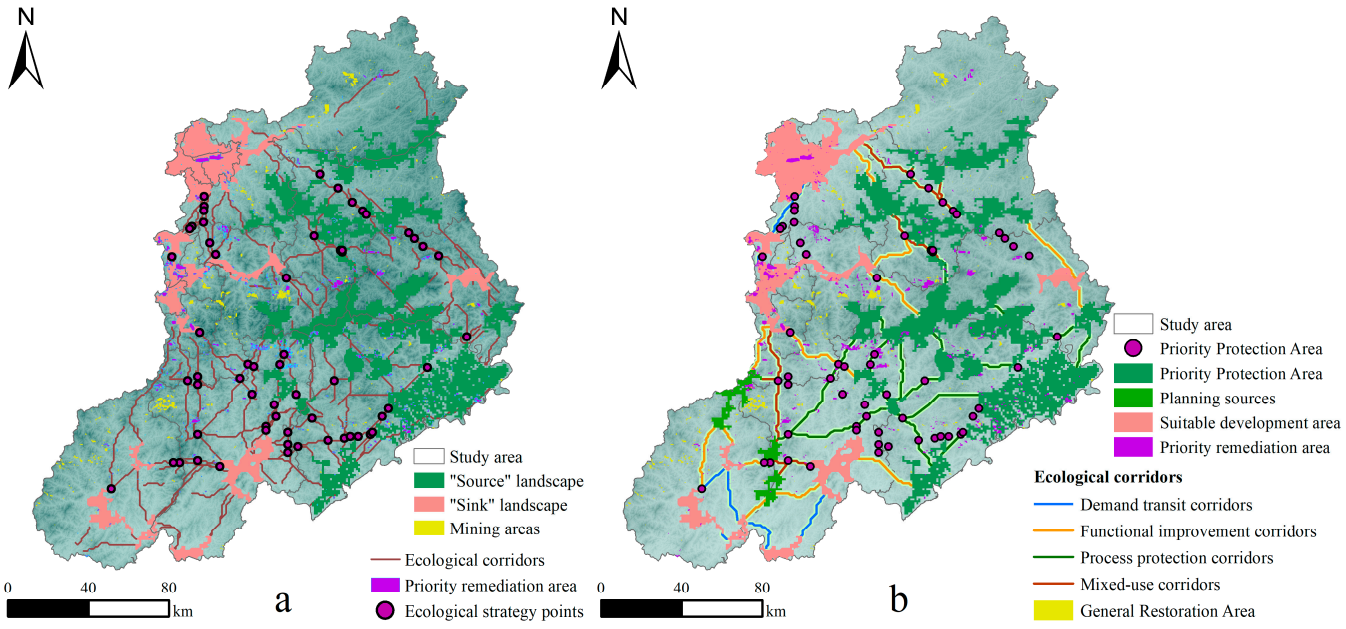


Figure 8. The optimization of ES supply-demand flow network.

4. Discussion

4.1. Effectiveness of ESs Flow Network Constructs

Existing studies have shown that the service flows of WY, SC, CS, and HQ are driven by different factors, and their flow media and diffusion modes are different. For example, the flow path of WY is considered to be driven by a combination of elements such as topography, rivers, and human activities, while the SC flow is mainly affected by slope, vegetation, and geomorphology [54,55]. For this reason, the ES flow network constructed in this study integrates the physical properties of ESs and the features of ESF. It aims to improve the landscape functionality through the integrated management of ESs, ensuring the balance of ESs supply and demand and preventing the destruction and pollution of ecosystems due to mining activities. In this paper, we identify ES sources and sinks through SOM clustering and ESDR analysis and use the physical characteristics of service flows to determine the supply-demand paths, i.e., corridors, and finally form the ES supply-demand flow network under different flow characteristics. The method combines ESF theory with physical characteristics to link ecosystem service flows with ecological networks, fully showing the spatial pathways of service flows [56]. Individual scholars identify ESFs' spatial paths and critical areas through the research paradigm of sources, sinks, corridors, and nodes. They focus on freshwater and food service flows, use rivers and transportation systems as connecting paths, determine the flow status of ESFs based on factors such as river flows, transportation costs, and human needs, and finally identify priority conservation [21,57]. However, it fails to explore other kinds of service flows and combine ESFs with mine rehabilitation, so it has some limitations.

In this study, we clustered the ESs supply-demand characteristics of grids based on SOM, identified source and sink, and realized the integrated management of ESs. The algorithm is being widely used in the field of ecosystem services, such as ecosystem service clustering [34], trade-off synergies [30], and ecological networks [16]. It is worth mentioning that the ES supply-demand network identified in this study is consistent with the spatial distribution of the landscape in the study area. Overlapping sources are mostly located in the eastern region (i.e., woodlands), and sinks are mostly located in the northwestern region (i.e., built-up land). The ecological conditions of the eastern forest are favorable, while the western region has limited forest and is a population concentration area. These socio-ecological elements seriously affect the level of ES supply and demand. With the advancement of urbanization, the trajectory of human activities keeps spreading, the forest is shrinking, the supply level of HQ, CS, and other services keeps decreasing, the demand gradually increases, and the difference between the eastern and western areas keeps intensifying. To alleviate the differences between different regions, this study constructs a flow network of ES supply and demand, aiming to promote regional sustainable development. Interconnected and dense corridors connect ecological sources in the east with sinks in the northwest, and the optimization network identifies a total of 47 priority flow paths and 60 ecological strategy points.

4.2. Restoration Strategies in the Perspective of Regional Ecological Integration

Currently, the optimization strategies of ecological networks mainly focus on increasing sources, reducing sinks, reducing corridor resistance, and protecting key nodes, while measures such as expanding sources and reducing sinks may restrict economic development and are difficult to implement when the spatial scope is limited [58,59]. Moreover, some scholars formulate optimization strategies based on complex network theory, which abstracts source areas and corridors simply as homogeneous nodes and edges, but landscape function assessment cannot be detached from their structural layout [60]. In general, existing research optimization strategies have failed to consider the overall characteristics of ES supply and demand and the landscape configuration within patches. In this study, we will first determine the ecological optimization direction in different areas based on the regional ES supply and demand level and socio-ecological conditions. Then, based on the landscape configuration and functional characteristics of BESDRS, the landscape

configuration structure will be determined to realize the integrated management of regional ecosystem services and mine re-greening. The optimized network can be divided into important protected areas, priority restoration areas, general restoration areas, and suitable development areas.

Important protected areas include sources, planned sources, ecological strategic points, major flow corridors, and their buffer zones. As the main source and key hub of regional ESs supply, it is necessary to follow the principle of ecological priority and fully protect the areas around the source and strategic points to ensure the supply capacity and flow efficiency of ESs [61]. In the study area, the ES are mainly synergistic with each other, the source and planned source are located in the protected area of the northeastern forest belt, which has a good ecological environment. The area relies mainly on ecosystem self-regulation and requires regular monitoring and assessment of the ecological situation, such as the establishment of remote sensing monitoring sites and environmental impact assessments. Strategic points are intersections of major flow paths, which are more numerous but smaller in size. It is necessary to adjust the patches according to the BESDRS2, and the direction of adjustment mainly depends on the degree of difference between the actual structure and the target clusters. At the same time, there are a certain number of open pit mines and subsidence areas around the site, which are the priority restoration areas. The main goal of this area is land leveling and mine re-greening, which requires a series of restoration projects, such as land remediation, soil reconstruction, and landscape restoration. The protection measures for the main corridors, which are the key paths for supply-demand flows, should be formulated according to the types and attributes of the corridors [62]. Process prevention, functional improvement, demand transition, and functional complex channels have different target priorities. For example, the function improvement and process prevention corridors of HQ and CS should be prioritized to ensure the supply capacity and reduce the disturbance of production activities in the mines. According to their corresponding ESF characteristics, the landscape structure of the corridors should be optimized to BESDR2, 3, and 5. Vegetation buffer zones and wetlands should be constructed for mines located in the corridors to block or absorb disturbing factors, stabilize the surrounding ecosystems and achieve the effect of process prevention.

General restoration areas and general protection areas refer to the mines outside of priority restoration areas and ecological patches outside of important protection areas, respectively. The distance between mines and ecological elements of the flow network is limited, which can easily hinder the material flow, information flow, and energy flow in the region. At the same time, according to the Northeast Forestry Belt Plan, the region will gradually close down small and highly polluting mines, so the general restoration area needs to establish a scientific and reasonable evaluation system, regularly monitor and evaluate the energy efficiency of mines, and measure the production efficiency. As the area is located in a geologically hazardous area, it is necessary to formulate a reasonable mining plan based on the monitoring and evaluation of the geological environment and the ecological value of mineral resources. The general protected area is dominated by forest, and it is necessary to satisfy the ecological objectives of regional planning, as well as to address the fragmented distribution pattern formed by the impact of urban construction and agricultural cultivation. In the future, the layout of cropland, construction land, and forest should be comprehensively coordinated to realize the coordinated development of industry, agriculture, and ecology. In addition, the imbalance between food supply and demand in the study area is more serious, and it is necessary to break the district boundaries to develop a unified spatial plan.

Suitable development areas are the overlapping areas of ecosystem service sinks and the mines within their scope. It is a concentration of human activities and a hotspot for HQ, CS, WY, and FP demand. This region serves as an economic production center with a high level of economic development. It is necessary to strengthen land use regulations based on economic construction, plan industrial layout and scale, and reduce the demand for ESs. Secondly, the entire life cycle of mineral resources should be developed and protected, the

mining process should be enhanced, industrial transformation should be implemented, and measures like restoration during mining should be taken to prevent land subsidence. Besides, establishing urban development boundaries is essential to prevent unchecked urban expansion into surrounding areas. This should encourage the effective use of land within the region, promote regional economic clustering, and allocate special funds for ecological monitoring and restoration.

4.3. Limitations and Prospects

The results of the study can provide a framework for the integrated management of regional ES flow and mine rehabilitation, but there are still some limitations and shortcomings. First, due to the limited accuracy of ecological monitoring data, only five representative ecosystems were selected for analysis in this paper, which is not comprehensive enough. It fails to take into account the supply-demand flow of ecological functions, such as windbreaks and sand fixation, and soil and water conservation. Secondly, the losses during the ES supply-demand flow and the spatio-temporal node characteristics were not quantitatively assessed, and there is a lack of precise analyses of the ES flow process. Finally, ESs often have scale effects, but the differences and connections of ESF at multiple scales failed to be analyzed. In the future, a multifunctional and cross-scale ESF quantification framework should be constructed to explore the flow characteristics and the degree of loss during the flow process to realize regional multi-scale ESF linkage management.

5. Conclusions

This study proposes a framework that links the supply and demand flows of ESs with ecological networks based on ecological monitoring data. It identifies ES supply areas, beneficiary areas, flow paths, and strategic points, determines the sequence and zoning of mine rehabilitation, and offers an effective strategy for the integrated management of ES flows and mine rehabilitation. Except for FP, ESs in the study area generally achieve a balance between supply and demand, with synergistic effects mostly found on the supply side, while the demand side exhibits more intense synergistic effects. The Ess supply area is concentrated in the eastern woodland, whereas the beneficiary area is distributed in the western populated agglomerations. The distribution of supply areas is influenced by natural conditions such as vegetation and elevation, while the changes in the location of beneficiary areas are mainly driven by human activities. There are significant differences in ES flow paths, with the number of corridors positively correlating with sources and sinks. The corridors of HQ are more uniformly distributed and numerous, whereas WY has the fewest corridors but the longest average length. The elements of different service flow networks are overlapping to identify key areas and functional zoning in combination with mine impacts to propose overall regional optimization measures, including landscape configuration adjustments in key areas, to achieve sustainable development of regional ecosystem services.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs16214021/s1. Table S1: Parameters of the InVEST model; Table S2: HQ module parameters; Table S3: Parameters of threat factors.

Author Contributions: Methodology, S.X. and Y.Z.; Software, S.X.; Data curation, S.X. and H.D.; Writing—original draft, S.X. and H.D.; Conceptualization, Y.Z.; Writing—review & editing, H.L. and Y.X.; Investigation, H.X. and D.L.; Supervision, H.L. and Y.Z. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: Hui Li, Hao Xu, Yiming Xing and Dan Li are employed by Chemical Geological Prospecting Institute of Liaoning Province Co., Ltd. The company played no role in the design of the study, the collection, analysis, or interpretation of data, the writing of the manuscript, or the decision to publish the article. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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