Diagnosis of Key Ecological Problems and Layout of Ecological Restoration Projects- A Case Study of the Aksu River Basin, China

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Abstract

The sustainable development of ecological environments is the basis of the sustainable development of inland river basins in arid areas with fragile ecological environments. The aim of our study is to diagnose the ecological problems of the Aksu River basin (ARB) and explore the ecological security pattern (ESP) and the layout and implementation path of ecological protection projects for mountains, rivers, forests, farmland, lakes, grasslands and deserts (MRFFLGD) in arid areas under different security levels. The Aksu River, the largest source of the Tarim River, was selected as the case study. The equivalent factor evaluation method (EFEM) was used to estimate the ecological service value (ESV), and the InVEST model was employed to quantify the ecological function indicators. By constructing the richness index, the ESV of the study area was measured spatially, and the ecological problems in the ARB were identified and diagnosed. Using cold/hot spot detection analysis and the minimum cumulative resistance (MCR) model, the ESPs at three security levels were constructed. The layout of ecological protection measures and the implementation path for MRFFLGD were studied. The results showed that the ESV of ARB showed an upwards trend from 1990 to 2018, and the three services of water conservation, waste treatment and soil formation and retention grew fastest. The value of ecosystem services in the study area in 2018 ranged from 5,390 yuan to 131,080 yuan/hm². The high-value areas were mainly located in the oasis and the northern mountainous area, and the low-value areas were mainly located in the desert area. The ecological source areas of high, medium and low safety levels were 1806.3 km², 3416.8 km² and 4804.32 km², respectively. Based on the spatial distribution of ESV in the ARB and the preliminary diagnosis of the basic ecological problems in the study area, three kinds of ecological protection engineering models, namely, conservation, natural restoration and assisted regeneration, were proposed for the four types of ecological protection zones. To provide a decision-making basis for ecological environmental management and regional sustainable development in the ARB, the optimization patterns of points (6 key ecological protection projects), lines (ecological corridors) and polygons (ecological source areas) were constructed. The results of this study can also serve as a reference for ecological environmental protection in other arid inland river basins.

Background

Ecological security guarantees that the ecological environment realizes regional security and social stability ¹. In 2012, the 18th National Congress of the Communist Party of China (CPC) prioritized eco-environmental progress and pursued green development under the guidance of Xi Jinping's thought on eco-civilization. Xi noted that "building the pattern of national ecological security" is an important approach for the construction of an ecological civilization ². Ecological security is of vital importance in national security ³. The state attaches great importance to national spatial planning and ecological protection and restoration projects for MRFFLGD ^{4,5,6}. The implementation of the construction of territorial ESPs involves the identification of key areas, such as ecological sources and corridors, that play a key role in the protection and maintenance of the ecosystem in a region ⁷. The spatial allocation of key ecological protection and restoration projects based on ecological security issues is also an important way to "optimize the ecological security barrier system, build ecological corridors and biodiversity protection network" according to the 19th National Congress of the Communist Party of China. The health degree of MRFFLGD is the external expression of the soundness of the ecological security barrier system. Therefore, the optimization of ESPs and comprehensive ecological protection engineering measures have become an important means to solve regional ecological environmental problems. It is also the premise of orderly ecological environmental protection work ⁸. The optimization of ESPs is to maintain the integrity of ecosystem structure and function and to provide comprehensive ecosystem services for a region ⁹. The optimization of the ESP of an inland

river basin in an arid area is the key to the sustainable development of oases and the national ecological security strategy¹⁰. Based on the evaluation of ecosystem service value (ESV) in the ARB, the richness index was used to measure the ESV in space and then identify and diagnose ecological environmental problems in the study area. It is of great practical significance to study the optimization of the ESP and the layout of ecological protection/restoration projects in the ARB according to the objectives of ecological protection planning.

There are several studies on ESP optimization based on the pattern of "ecological source identification - resistance surface construction - ecological corridor construction". The MCR model^{9,11,12,13,14,15,16}, circuit network model^{17,18,19,20,21,22,23}, and multiple combination model^{24,25,26} are widely used. Related studies on the construction and optimization of ESPs are aimed at cities and urban areas^{16,22,27,28}, and more research is focused on natural ecological units such as the Loess Plateau²⁹ and Qinghai-Tibet Plateau³⁰, Shule River basin³¹, Poyang Lake²⁴, and Chao Lake²⁵. Furthermore, at the practical level, the demarcation of ecological protection red lines^{9,32}, ecological environment restoration²³ and the construction of ESPs of nature reserves³⁰ are common in the study of ecological environments. As the natural environment and utility on which human beings depend for survival, it is of great significance to scientifically evaluate the spatial and temporal patterns and interaction mechanisms of ecosystem services to determine the basis of the regional ecological environment and construct regional ESPs. In recent years, there has been an increasing number of studies based on ecosystem service assessments^{33,34,28}. Therefore, most studies have used the equivalent factor method (ESV unit area of Chinese terrestrial ecosystems), which was improved by Xie³⁵ based on Costanza's³⁶ research, to estimate the ESV. However, the estimated value of ecosystem services by Xie³⁵ was static rather than dynamic, and the estimated results did not reflect the changes in ESV with social, economic and natural environmental conditions well. Although research on ecological security patterns has made much progress, there are still some deficiencies. Building an ESP and guiding regional land and space development is an important technique to ensure regional ecological security and stability to achieve sustainable development⁹. Improving and stabilizing ecosystems plays a fundamental and strategic role in ensuring national ecological security. Hence, it is necessary to carry out a dynamic assessment of ESV at the grid scale to identify ecological environmental problems. Thus, promoting the optimization of ESPs and the layout of ecological protection/restoration projects according to ecological protection planning objectives are essential.

In the zones oriented toward the National Plan for Major Function, "two barriers and three belts" are the main parts of the national ecological security strategy. On the basis of this strategic pattern, ecological protection and restoration projects of MRFFLGD can promote the maintenance and restoration of ecological space and ecological function. The ARB belongs to the important northern sand control zone in the "Three Belts", and it is also the water conservation area of the Tianshan Southern vein and the agricultural product supply function area of the Aksu Oasis. Additionally, the "Ecological Protection and Restoration Project Guide of Mountains, Waters, Forests, Fields, Lakes and Grass" noted that "the systematic integrity of the natural ecosystem should be comprehensively considered, and relatively complete natural geographical units such as rivers, lakes, basins and mountains" should be the focus of ecological protection and restoration. The ARB has a unique mountain-oasis-desert ecosystem, forming a unique landscape and spatial pattern in arid areas³⁷. The Aksu River provides 74% of the water of the Tarim River and occupies an important position in the ecological security pattern of the Tarim Basin³⁸. In recent years, with the continuous expansion of the Aksu artificial oasis area, the fragile ecological environment has been affected to some extent, and soil desertification, grassland impoverishment, soil and water loss and other ecological security problems have become worrying.

Thus, the main objectives of this paper were to (1) measure the dynamic ESV at the grid scale; (2) identify and diagnose the ecological problems in the ARB; and (3) construct a network ESP that varies by point (ecological sources) – line (ecological corridors) - polygon shape to high - middle - low levels (different security levels). The results provide a reference for optimizing the ecological spatial structure, ensuring regional ecological security and promoting regional sustainable development in ARBs.

Materials And Methods

Study area.

The ARB is located in the alluvial plain of the Northwest Tarim Basin (Figure 1). It is the main stream of Tarim river. The terrain features high values in the north and low values in the south and tilts from northwest to southeast. The Aksu Oasis is an oasis developed by the Aksu River with a typical temperate continental climate, drought and little rain, intense evaporation, long sunshine duration and large temperature difference between day and night. In this region, agriculture is a typical oasis irrigated agriculture that completely relies on surface irrigation projects and groundwater extraction. It is an important production base for grain, cotton, melon, and fruit crops in Xinjiang . In recent years, economic development in the Aksu area has led to a significant increase in water consumption and water demand in the basin and a continuous decline in groundwater level, which has affected agricultural production and ecosystem security, resulting in the gradual degradation of important ecosystems .

Data resources.

The data in this paper are mainly divided into the following categories:

The statistical data: The statistical data used in this study are mainly from the statistical yearbook of Aksu, the statistical yearbook of Kizilsu Kirgiz Autonomous Prefecture.

The land use data (1990, 2005, 2018), net primary productivity (NPP) data, digital elevation map data, climatic (temperature, precipitation) raster data, and normalized vegetation coverage degree data (NDVI) used in this study are mainly from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (available at <http://www.resdc.cn>). The main types of land use are cultivated land, forestland, grassland, water area, unused land, construction land and corresponding to "China's terrestrial ecosystems services equivalent unit area" of farmland, forest, grassland, water, and unused land, with 5 kinds of ecosystem types, construction land neglected, and the value of ecosystem services set to 0.

The soil thematic data: The soil project data used in this study are mainly from the Chinese Soil Science Database (available at <http://vdb3.soil.csdb.cn/>).

The spatial resolution of the above data is 1 km*1 km.

Ecosystem service value calculation.

Ecosystem services (ESs) refer to the benefits obtained directly or indirectly from ecosystems for human survival or improvement of quality of life , and the quantitative evaluation of their value is of great significance to maintaining regional ecological security and promoting the coordinated development of the regional economy and environment

¹⁰. Xie et al improved the equivalent factor method of the unit area value to estimate the ESV of the ARB. The total output and planting area of grain crops in the study area in 1990, 2005 and 2018 were obtained from the statistical yearbook. The ESV of the ARB was calculated as follows (1):

$$E_a = \frac{1}{7} \sum_{i=1}^n \left(\frac{m_i \times P_i \times q_i}{M} \right)$$

1

Note: The equivalent value of a standard ecosystem service is worth seven times the economic value of grain produced per unit area in that year.

In Equation (1), E_a is the value of the unit equivalent factor; N is the number of types of grain crops, m_i is the sown area of grain crop i ; p_i is the unit price of grain crop i , q_i is the unit yield of grain crop i , and M is the total area of grain crop N planted in the research area.

Combined with the actual situation of the study area, the coefficient of the ESV per unit area in Xie et al.'s "Ecological Service Value per unit area in China" ³⁵, was revised twice:

1) Modification of the biomass factor based on regional differences using the value of 0.58 in Xinjiang .

2) Revision of the coefficient of social development. An ESV is closely related to social and economic development. Each function of human well-being that ESs flow from natural capital is not immutable; it functions through interaction with human capital, social capital and built capital ³⁶. Considering the regional social and economic development level of the ARB, the ESV coefficient was adjusted a second time. The S curve model was used to characterize its development trend , as shown in Equations (2) and (3).

$$I = \frac{L}{1 + e^{-(1/E_n - 3)}}$$

2

where I represents the social development coefficient corresponding to the willingness to pay for functions provided by the real ecosystem; L represents the willingness to pay for ecosystem functions under a state of abundant wealth, herein regarded as 1; e is the natural constant; and E_n is the Engel coefficient.

$$K = \frac{l'_{ARB}}{l'_{\text{The Xinjiang average}}} \quad (3)$$

where l' and I represent the average willingness to pay for functions provided by the real ecosystem of Xinjiang and the ARB, respectively.

According to Equations (2) and (3), the revised standard equivalent factor value is shown in Equation (4):

$$E'_a = 0.58 \times K \times E_a \quad (4)$$

The ESV coefficients of different land use types are calculated as follows (Equation 5):

$$VC_{ki} = E_a' \times EC_{ki}$$

5

where VC_{ki} represents the coefficient of ecosystem service type k of land use type i . EC_{ki} is the equivalent factor of ecosystem service type k of land use type i . The sum of ESV of n types of land use is shown in Formula (6)

$$ESV = \sum_{k=1}^n (A_k \times VC_{ki})$$

6

where A_k is the area of land use type i . Using the above formula and the area of 5 land use types in the ARB in 1990, 2005 and 2018, the ESVs for 5 land use types could be calculated.

To verify the rationality of ecosystem service value estimation, it is necessary to examine the sensitivity of ESV to changes in VC. Therefore, the coefficient of sensitivity (CS) was used to quantify the degree of influence of ESV on changes in VC²⁸. The CS is shown in Formula (7):

$$CS = \left| \frac{(ESV_j - ESV_i) / ESV_i}{(VC_{jk} - VC_{ik}) / VC_{ik}} \right|$$

7

where ESV_i and ESV_j are the values of ecosystem services before and after adjustment, respectively, and VC_{ik} and VC_{jk} denote the value coefficients for land use type k before and after adjustment, respectively. When $CS > 1$, it indicates that ESV is elastic relative to VC; when $CS < 1$, it indicates that ESV is inelastic relative to VC, and the estimation result of ecosystem service value is credible.

Spatial measurement of ecosystem service value.

In this paper, we propose the spatial importance index R_i of ESs, which avoids the traditional method of estimating ESV based on the homogeneity distribution of various ESs on the same land use type and protects the sensitive function of ESV. Therefore, this paper used 2018 as an example to measure the spatial distribution of ESV in the study area.

The spatial accuracy of the ecological service index data in the study area was set as a 1 km×1 km grid, and the indices of each ecosystem service function indicator were quantified in grid units to construct the spatial importance index of ecosystem services, as shown in Table 1. Standardizing the importance index of each service function. The larger the value is, the more important the ecological service space value referred to by this index is (Equation 8):

$$R_i = \frac{C_{ki}}{C_i} (k = 1, 2, 3 \dots n)$$

8

where R_i represents the spatial importance index of the i -th service in the k -th grid, C_{ki} is the spatial aggregation degree of the i -th service in the k -th grid, C_i is the mean spatial aggregation value of the i -th service, and n is the number of grids.

After adjusting the importance index and combining it with the total area of the study area, the revised spatial grid map of each single ESV was obtained, and the spatial distribution map of each single ESV was superimposed to obtain the total spatial distribution map of ecosystem service value in ARB in 2018 Equation 9.

$$ESV = \sum_{i=1}^9 \left(\sum_{k=i}^n R_{ki} \times \frac{ESV_i}{A} \right) \quad (9)$$

where ESV is the revised total ESV, ESV_i is the ESV of item i , and A is the total area of the study area.

Table 1

Key ecosystem service indicators and their quantification in the ARB

Construction of ecological security pattern.

The construction of ecological security patterns is an important research topic in landscape ecology ⁴⁵, guiding the practice of ecological civilization. The construction of ESPs is based on the diagnosis of ecological problems, guided by ecological protection objectives, and the use of scientific methods to identify ecological sources and ecological corridors. Key ecological protection projects should be planned and laid out in view of ecological problems, which is the perfect combination of theoretical and practical aspects of ecological security barrier system construction. This paper is based on the spatial measurement of ESV in the ARB. The cold-hot analysis method was employed to identify ecological source areas under high, medium and low ESPs, and the corresponding ecological corridors of high, medium and low ecological source areas were calculated by the cumulative minimum resistance model (MCR) ^{32,11,12,13,14,15,16}. Considering the community with a shared future of MRFFLG, ecological problems were diagnosed in the low-value area of a single ESV. The ESP of the ARB was obtained by studying the layout of key ecological protection projects combined with ecological protection zones.

Identification of ecological source.

Ecological sources are the source points of species diffusion and maintenance, and they can provide key ecological services, provide continuity and integrity of landscape patterns, and prevent ecosystem degradation ^{29,32}. Based on ArcGIS cold/hot spot analysis tools, we extracted ARB ecosystem service values of 99%, 95%, and 90% of the hot spots in the space as low-, medium- and high-level ecological security sources. The connotation of ecological source areas is the continuity and integrity of the landscape, which must reach a certain scale to effectively isolate the external interference to the source area ^{11,12,13,14,15}. In this study, patches less than 0.5 km² were removed as ecological sources ¹⁰.

Ecosystem service	Indicators	Index quantification
Gas regulation	Oxygen release	$W_{O_2} = NPP \times 2.2 \times 1.19$ ⁴⁷
Climate regulation	Carbon storage	Farmland carbon storage, grassland carbon storage and forest carbon storage were estimated based on primary net productivity (NPP), while other land carbon storage was ignored ⁴⁸
Water conservation	Water yield	InVEST model was used to calculate water conservation services
Soil formation	Soil retention	The soil erosion equation RUSLE of InVEST model, the difference between bare soil loss (RKLS) and soil loss (USLE) with management measures and vegetation cover is soil conservation force (RUSLE) ⁴⁹ . $USLE = R * L * S * C * K$ $P, RKLS = R * L * K S$. R is rainfall erosivity factor, K is soil erodibility factor; LS is slope length & slope factor; C is coverage and management factor; P is the factor of soil and water conservation engineering measures.
Waste treatment	Simulations of the mean annual river runoff	Annual average simulated runoff was used as the waste treatment index based on (DEM) and ArcGIS hydrological analysis module
Biodiversity conservation	Habitat quality	The habitat quality module in InVEST model ⁵⁰
Food production	Soil organic matter content	Extraction of soil organic matter content from soil thematic data
Raw material	Proportion of forested area to the study area	"Forestland" was assigned as 1, and other areas were assigned as 0 to map a 1 km grid picture
Recreational culture	Tourism and cultural central classification	Forest Park, urban park, important public service center, important cultural activity center and other areas were assigned as 1, 0.7, 0.5, 0.3 and 0, respectively, according to their importance. The importance distribution map of tourism and cultural centers in the study area was obtained by inverse distance interpolation

Identification of ecological corridors.

Ecological corridors are channels for ecosystem service communication and flow ²⁹. Using the MCR model, based on the ecological source areas of high, medium and low levels, the reciprocal of ESV is regarded as the resistance surface; that is, the higher the ESV is, the smaller the resistance value is. Through the cost distance in the ArcGIS spatial analysis tool, potential ecological corridors at high, medium and low safety levels were obtained. The ecological security pattern of the ARB at three security levels was constructed. The MCR model formula is as follows Equation 10:

$$MCR = \text{fmin} \sum_{j=n}^{i=m} (D_{ij} \times R_j)$$

where MCR is the value of minimum cumulative resistance, f_{min} represents the positive correlation between the minimum cumulative resistance and the ecological process, D_{ij} is the spatial distance between ecological source unit j and landscape unit i , and R_i denotes the resistance coefficient of landscape unit i to species movement.

Results

Analysis of ecosystem service value change.

The economic value of natural grain yield per unit farmland in 1990, 2005 and 2018 in the ARB was 973.73 yuan/hm², 1473.78 yuan/hm² and 2588.42 yuan/hm², respectively. The annual average economic value was 1678.64 yuan/hm². After two coefficient modifications (biomass factor adjustment and social development coefficient adjustment), the ecological service value coefficient applicable to the study area was obtained, and the results are shown in Table 2.

Table 2

Ecosystem service value (ESV) coefficients per unit area of different land use and land cover change types in the ARB, 2018

Ecosystem function	Land use types Corresponding ecosystem service types	Forest	Grassland	Farmland	Water	Unused land
Regulating function	Gas regulation	6096.41	2116.81	1016.07	719.72	84.67
	Climate regulation	5743.61	2201.81	1368.87	2907.09	183.46
	Water conservation	5771.83	5771.83	1086.63	26488.35	98.78
	Soil formation	5673.05	5673.05	2074.47	578.59	239.91
Supporting function	Waste treatment	2427.28	1862.79	1961.58	20956.42	366.91
	Biodiversity conservation	6364.54	2638.96	1439.93	4840.44	564.48
Provisioning function	Food production	465.7	606.82	1411.21	747.94	28.22
	Raw material	4205.4	508.03	550.37	493.92	56.45
Cultural function	Recreational culture	2935.31	1227.75	239.91	6265.76	338.69

According to the area of each type of land use in the study area, the value of each ecological service and its change during the study period were obtained (Table 3). The total ESV in the ABR was 17.794 billion yuan in 1990, 26.573 billion yuan in 2005 and 46.451 billion yuan in 2018, showing an upwards trend. The value of water conservation was the highest in a single ecological service, accounting for 16% of the total ESV in that year.

From 1990 to 2018, the value of water conservation grew the fastest, with an increase of 4.7 billion yuan. The values of food production, raw materials and entertainment and culture ecosystem services were the lowest, and the

total value of these three ecosystem services was approximately equal to the value of biodiversity conservation. From 1990 to 2018, the average annual change rate of each ESV in the ARB was 31.84%, showing a fast growth rate.

In 1990, 2005 and 2018, the change rate of ESV increased year by year. Significant differences in value were identified among the four functions. From 1990 to 2018, the growth rate of ESV of water conservation, waste treatment, and soil formation increased by approximately 160%, while the growth rate of raw material and food production remained at approximately 40%. During the study period, the change rate of water conservation ESV was the fastest, with a growth rate of 251%, while the raw material value was the lowest, with a growth rate of 17.29%. Overall, the growth rate of ESV from 2005 to 2018 was more than three times that from 1990 to 2005.

Table 3

Ecosystem service values (ESVs) in the ARB in 1990, 2005 and 2018 (/10⁸ yuan, %)

	GR	CR	WC	SF	WT	BC	FP	RM	RC	Total
1990 a	19	21.26	29	28.44	26.32	27.12	6.84	6.09	13.87	177.94
2005 a	27.73	31.42	43.72	41.94	40.41	40.05	10.92	9.2	20.34	265.73
2018 a	48.04	54.75	76.43	73.08	71.39	69.63	19.86	16.23	35.1	464.51
1990-2018 changes in ESV	29.04	33.49	47.44	44.64	45.07	42.51	13.02	10.14	21.23	286.57
1990-2018 ESV change rate	103.72	119.6	169.42	159.42	160.97	151.82	46.48	36.23	75.28	1023.48
1990-2005 ESV change rate	48.51	56.45	81.79	74.98	78.29	71.85	22.67	17.29	35.94	487.76
2005-2018 ESV change rate	156.23	179.44	251.65	239.56	238.3	227.51	68.73	54.09	113.54	1529.05
Note: Gas regulation (GR), Climate regulation (CR), Water conservation (WC), Soil formation (SF), Waste treatment (WT), Biodiversity conservation (BC), Food production (FP), Raw material (RM), Recreational culture (RC)										

As shown in Table 4, the coefficients of sensitivity of ecosystem services in the ARB in 1990, 2005 and 2018 were all less than 1, indicating that the calculated results of ecosystem services were inelastic and that the research results were reliable.

Table 4

Results of the sensitivity coefficient in the ARB

		Forest	Grassland	Farmland	Water	Unused land
The coefficient of sensitivity ΔCS	1990	0.07	0.72	0.09	0.06	0.05
	2005	0.07	0.68	0.13	0.06	0.06
	2018	0.07	0.66	0.15	0.06	0.06

Priority index of ESV.

The priority coefficients (Ri) of ESs in the ARB are shown in Table 5. The Ri values of water conservation, waste treatment, soil formation and biodiversity conservation were above 1.3, which showed the rapid rate change of the Ri. The rate of change of Ri showed that food production and raw materials were relatively weak. The importance coefficient of food production and raw materials was less than 1/3 of the water conservation function.

Table 5

Ecosystem services priority index in the ARB

	FP	RM	GR	CR	WC	WT	SF	BD	RC	Average value
The rate of change of Ri	46.48	36.23	103.72	119.6	169.42	160.97	159.42	151.82	75.82	113.72
Ri	0.41	0.32	0.91	1.05	1.49	1.42	1.4	1.34	0.67	1
Note: Gas regulation (GR), Climate regulation (CR), Water conservation (WC), Soil formation (SF), Waste treatment (WT), Biodiversity conservation (BC), Food production (FP), Raw material (RM), Recreational culture (RC)										

Spatial measurement of ESV based on the priority index.

Figure 2 depicts the standardized index value of each ecosystem service function of the ARB in 2018. Combining the priority index of each ecosystem service type, we obtained the spatial distribution map of the ARB ecosystem services, as shown in Figure 3. It can be concluded that the ESV of the ARB is 5390-131080 yuan/hm², and the average value of ecosystem service value of approximately 20% patches was 24730 yuan/hm² in 2018. The areas with the highest ESV were mainly distributed in the oasis area and the mountains of the northern basin, including the red line zone of water conservation and ecological protection in the Tianshan Southern Vein, the red line zone of windbreak sand fixation ecological protection in the Toshgan River, and the biodiversity maintenance ecological reserve, glaciers and permanent snow zone. These areas have abundant water resources without too much disturbance from human activities, and the ecosystems are relatively stable. Areas with a low ESV were mainly concentrated in the desert and Gobi area, such as desert areas in northern and southern Aheya town, Wushi County, and Gobi in eastern Aksu Oasis. It is worth noting that scattered low-value areas of ecosystem service value existed in oases, such as urban and rural residential land, and industrial and mining land were identified as low ESV areas. Due to its large population density per unit area, land use intensity and ecological environment pressure are relatively high, so the ESV is low.

Ecological security pattern construction based on ESV.

The cold/hot spot detection method was used to extract alternative ecological source areas of low, medium and high safety levels in the ARB. The corresponding ecological corridors of low, medium and high ecological security sources were obtained by the MCR model, as shown in Figure 4.

According to the constructed ESP results, although the number of patches in the ecological source was large, other ecological sources were scattered, except for the water conservation zone in Tianshan and the biodiversity conservation ecological reserve in the northern ARB. At the low level of ESP, there were 11 source patches with a total area of approximately 1806 km². They were mainly concentrated in the northern Tianshan Forest Park, Tomur Peak Nature Reserve (National Public Welfare Forest), windbreak sand fixation ecological protection zone of the Toshgan River, National Wetland Park of the Duolang River and Kukexiale of Aheqi County, which are prohibited development zones, ecological protection red line zones and other ecological protection lands. At the medium level of ESP, there were 27 source patches with a total area of approximately 3416 km². On the basis of the ecological source patches of low levels of ESP, 1610 km² was increased, and the number of patches increased by 16. The main areas with an increase were found along the periphery of the ecological source of low levels of ESP, the water system of the main stream of the Aksu River and the snow-covered area of Aheqi County in the western part of Tianshan Mountain. High levels of ESP source coverage, medium and low levels of ecological sources, natural forests and shrubbery with canopy densities greater than 30% on Kalatike Mountain in southern Aheqi County were added at a high level of ESP of ecological sources. The number of ecological source patches increased by 8, and the area increased by 1387.6 km². In summary, from a low level of ESP to a high level of ESP, the number and area of ecological sources increased, and the ecological corridor expanded from the axis to the network.

The three levels of ESPs are the key to guaranteeing the ecological security of the ARB. This work can provide some reference for ecological environmental protection in the ARB, e.g., the alluvial fan plain between the Telan River and Kalayurkun River in the eastern part of the oasis. Due to its large evaporation and strong infiltration of surface water, the phenomenon of river flow interruption is serious in the dry season, and the river in this region should be considered in the dry season. Therefore, ecological corridors should be constructed to realize the effective connection of ecological sources and improve the ecological security of the whole region.

The ecological problems were diagnosed in the ARB.

Based on constructing the ESP and the value of each ESV indicator, the main ecological environmental problems, such as the degradation of vegetation, water and soil loss, degradation of soil quality, and environmental degradation, were diagnosed. We decomposed the ecological issues to the community with a shared future of MRFFLGD in each factor. In this paper, 8 kinds of ecological issues were selected to construct the diagnostic index system of ecological problems in the ARB (Table 6). According to the results of our quantitative assessment of ESs, the value of ecosystem functions was divided into 3 grades from high to low, which indicate the risk level of ecological problems. From the perspective of ecological protection and restoration of MRFFLGD, according to the number of restoration objects of MRFFLGD involved in each ecological index, the index weights were determined, and the corresponding ecological problems of each type of land were taken into account to divide the risk level.

Table 6

Diagnostic index system of ecological problems in the ARB

Ecological problems	Type	Index name/Weight	Level of risk
Water and soil loss	Mountains	Soil retention/0.3	Slope length & slope risk level: LR0-0.61MR (0.61-1.73) HL (1.73-5.37) Natural Breaks
	Rivers		Water area risk level: LR-Lakes, reservoirs and ponds, MR- Flood land, HR-Glaciers and areas of permanent snow
	Forests		Forests risk level: LR-Woodland, shrubbery, MR-Sparse woods, HR-Other woodland
Insufficient water resources carrying capacity	Rivers	Water yield/0.1	Water production risk level: LR-Glaciers and areas of permanent snow, MR-Lakes, reservoirs and ponds, HR- flood land
Inadequate water conservation	Lakes		Water production risk level: LR-Glaciers and areas of permanent snow, MR-Lakes, reservoirs and ponds, HR- flood land
Vegetation degradation	Forests	Forest carbon storage/0.1	Conservation water sources risk level: HR-wetland and reservoir, MR- other types of water
The grassland is barren	Grasslands	Grassland carbon storage/0.1	Forest carbon storage risk level: LR-Woodland, shrubbery, MR- Sparse woods, HR- Other woodland
Degradation of soil quality	Farmland	Soil organic matter content/0.1	Forest carbon storage risk level: LR- High coverage grassland, MR-moderate coverage grassland, HR- low coverage grassland
Environmental degradation	Mountains, Rivers, Forests, Farmland, Lakes, Grasslands, Deserts	Habitat quality/0.5	Soil organic matter content risk level: LR-paddy fields, MR-upland, HR-Soil organic matter content 5 g/kg of upland
Land desertification			Habitat quality risk level: LR0.65-0.99MR (0.3-0.65) HL (0-0.3) Land desertification risk level: HR- sandy land and bare land of unused land are high risk, MR: Other types of unused land
Note: Low risk (LR), Middle risk (MR), High risk (HR)			

Ecological protection zoning and key engineering measures.

We started with the quantifiable indicators corresponding to ecosystem service functions, the ecological problems in the ARB were identified, and the ecological risk levels of the corresponding regions were divided. The ecological protection zones of the ARB were divided into the following four categories: windbreak sand fixation zones, water and soil conservation zones, water resource conservation zones and agricultural product ecological security zones (Figure 5). The ecological protection zoning delineated in this paper was basically consistent with the ecological environment protection planning of the Aksu River basin (2015-2025), indicating that the ecological protection zoning delineated in this study was reasonable.

The quantitative indices in Figure 2 and Table 5 were multiplied and superimposed to obtain the main ecological high-risk distribution areas of various land uses in the study area (Figure 6). The key ecological engineering layout of the study area was carried out on the basis of the distribution area of soil and water loss area, insufficient water resource conservation area, insufficient water resource carrying capacity area, vegetation degradation area, barren grassland area, poor distribution area of cultivated land quality (soil organic matter content <0.5 g/kg), habitat quality <0.1, and desertification high-risk area.

To guide the ecological protection and restoration of MRFFLGD, we suggest that each type of ecological protection and restoration unit in the study area should adopt the protection and restoration mode of conservation, natural restoration and auxiliary regeneration ⁵¹. Therefore, in view of the ecological environmental problems and the spatial distribution of high-risk areas in the ARB, we further put forward suggestions on the spatial distribution of key engineering measures in the area of ecological protection (Figure 7, Table 7).

Table 7

Ecological protection zoning and key project measures in the ARB

Ecological protection zone	Ecological problems	Ecological conservation/restoration mode	Engineering measures
Water and soil conservation zone	Water and soil loss, Insufficient water resources carrying capacity, Inadequate of water conservation, Vegetation degradation	Protection and conservation, Auxiliary regeneration	Key project of water and soil loss prevention and control Key project of ecological construction of forestry and grassland
Water source conservation zone	Water and soil loss, Inadequate of water conservation, Insufficient water resources carrying capacity	Natural regeneration, Protection and conservation	Key project of water source protection
Windbreak and sand-fixation zone	Insufficient water resources carrying capacity, Vegetation degradation, Land desertification	Auxiliary regeneration	Key project of ecological construction of windbreak and sand fixation in oasis desert ecotone
Agricultural products ecological security zone	Environmental degradation Degradation of soil quality Inadequate of water conservation	Auxiliary regeneration	Key project of soil improvement of cultivated land in irrigated area Key project of river regulation in irrigation area

Key project of water and soil loss prevention and control: In soil and water conservation areas and areas with serious soil erosion, digging desert vegetation and destroying forests and meadows are strictly prohibited. The ecological environment should be protected around river banks, reservoirs and permanent snow areas. Overloading of grassland is strictly prohibited, and the project to return grazing land to grassland should be vigorously promoted.

Key project of ecological construction of forestry and grassland: In the areas where vegetation is severely damaged, such as natural forests, *Populus euphratica* forests and natural grasslands, measures of forest and grassland

conservation should be adopted to ensure biodiversity by means of natural restoration and artificial restoration projects.

Key project of water source protection: All development and construction activities in glacier areas and areas with permanent snow cover are prohibited. Timely closed mountain afforestation, pauses in grazing or periodic grazing bans and seasonal rotation grazing measures should be adopted. The construction of water and soil conservation forests can help to conserve water resources, improve the water and soil environment, and ensure the balance of water resources in downstream agricultural areas and watersheds.

Key projects of ecological construction of windbreak and sand fixation in oasis desert ecotone: In ecotone, shrub species with drought resistance and alkali resistance can be selected to construct a mixed ecological barrier of shrubs and grass, forming an independent and symbiotic ecosystem of desert-oasis.

Key project of soil improvement of cultivated land in irrigated area: Aiming at the areas with poor soil quality in the ARB, comprehensive remediation (physical-chemical remediation and biological remediation technology) was carried out to improve farming efficiency and increase land productivity.

Key river regulation project in irrigation areas: through channel transformation, we can adjust river runoff, recharge groundwater, maintain the regional water balance, and coordinate agricultural and ecological water use in irrigated areas.

Discussion

Changes in ecosystem service values.

Our results showed that from 1990 to 2018, the value of ecosystem services in the ARB region showed an increasing trend, from 17.794 billion yuan to 46.451 billion yuan. The change in ecosystem service value in the ARB was due to the change in land use type, which was similar to the results of several previous studies^{31,34,53,54}. However, the increase in the total ESV was caused by the adjustment of the ecosystem service value coefficient with the development of society and the economy. This paper calculated only the changes in ESV in the ARB in 1990, 2005 and 2018, and the interannual changes in ESV were not clear. The improvement of water conservation capacity in the ARB from 1990 to 2018 may be related to the project of ecologic water conveyance of the Tarim River^{38,39,40} and the Grain for Green Program¹³. It is noteworthy that value input is not considered in most studies on ecosystem service valuation. We pay too much attention to the human welfare provided by ecosystem services, and the input part is seriously neglected. For example, the material and human cost of planting should be excluded from food production, which is also the main reason for the high estimated value of ecosystem services.

The effectiveness of constructed ESPs.

The construction of ESPs has a certain reference value in regional overall ecological security and ecological environment protection. The ecological restoration measures proposed by us can actively restrain local ecological degradation. However, the investment and scale of each ecological restoration project need further research to ensure the landing and implementation of each ecological restoration and protection project⁴. Landscape connectivity should also be considered to explore the multifunctional potential of local landscapes and enrich the elements and functions of ecological security barriers on the basis of ecological protection. It not only improves the

supply capacity of ecosystem services but also promotes the coordinated development of ecological protection and the regional economy ⁴⁹.

Limitations and future work.

The value evaluation method based on the value equivalent factor of unit area has the advantage of facilitating the comparison and analysis of the dynamic change in value among different ecological service functions. In this paper, we adjusted the service value of the ecosystem per unit area and effectively improved the value evaluation results based on the equivalent factor method. In addition, this paper considered only the evaluation of land use classification results ¹⁷. A more detailed classification of land types would be more conducive to improving value assessment and deepening our understanding of the value of different ESs ^{34,48}. Furthermore, human activities are becoming increasingly diverse and disorderly, especially in arid areas, which affect ecosystem services more obviously. Spatial quantitative analysis and index refinement research on different human activities and ESs should be strengthened in future studies ³⁷.

Conclusion

Taking the ARB as the research object, this paper estimated the value of ecosystem services by using the equivalent factor method, constructed the priority index, quantified the ecosystem services function index based on the InVEST model, and measured the spatial value of ESs. Based on the reconstruction results, the ESP at three safety levels was established by using cold-hot spot detection analysis to identify the ecological sources and the MCR model to calculate ecological corridors, and the ecological environmental problems diagnosed in the ARB were studied to carry out the layout of ecological protection/restoration engineering measures. The main conclusions were as follows: (1) the ESV of the ARB increased from 1990 to 2018, and the following three ecosystem service functions increased the fastest: water conservation, waste treatment and soil formation. (2) The reconstructed ESV ranged from 5390 yuan/hm² to 131,080 yuan/hm², and the high-ESV area was mainly concentrated in the oasis and northern mountainous areas, while the low-ESV area was mainly concentrated in the desert area. (3) The ecological source areas of high, medium and low safety levels were 4804.32 km², 3416.8 km² and 1806.3 km², respectively. (4) Based on the spatial distribution of ESV and the basic ecological problems in the ARB, four types of ecological protection zones were divided, including conservation, natural restoration and auxiliary regeneration, which were the main conservation engineering modes. The optimization patterns of points (6 kinds of key ecological protection projects), lines (ecological corridors) and polygons (ecological sources) were constructed, which can provide a decision-making basis for ecological security planning in the ARB.

Declarations

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Author Contributions

L.X. designed and carried out the majority of the research. H. W and S. L cooperated in the research, providing input throughout and reviewing details. Y.L. is the academic adviser. All authors reviewed the manuscript.

Additional Information

Supplementary information

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Figures

Figure 1

Location and topography of the study area. (Software: ArcMap 10.2.0, <http://www.esri.com>)

Figure 2

Single ecosystem services and their values in the ARB, 2018 (Software: ArcMap 10.2.0, <http://www.esri.com>)

Figure 3

Spatial distribution of ESs and their values in the ARB, 2018 (Software: ArcMap 10.2.0, <http://www.esri.com>)

Figure 4

Identification of ecological sources and corridors at different levels in the ARB (Software: ArcMap 10.2.0, <http://www.esri.com>)

Figure 5

Ecological protection zoning of the ARB (Software: ArcMap 10.2.0, <http://www.esri.com>)

Figure 6

High-risk area of ecological problems in ARB (Software: ArcMap 10.2.0, <http://www.esri.com>)

Figure 7

Layout of ecological protection projects in the ARB (Software: ArcMap 10.2.0, <http://www.esri.com>)