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Spatiotemporal Evolution and Influencing Mechanisms of Ecosystem Service Value in the Tarim River Basin, Northwest China

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Abstract: The Tarim River Basin (TRB) is situated in the hinterland of northwest China, which is an extremely arid and fragile ecological zone. In recent years, the region's ecological civilization construction has been facing huge challenges that are exacerbated by climate change and human activities. In order to verify the current ecological status of TRB, this paper explores the spatial and temporal variation in ecosystem service value (ESV) and the impact mechanism based on LUCC data from 2000 to 2020, using the adjusted unit area value equivalent method, the elasticity index method and the geo-probe analysis method. The results show that: (1) the ESV of the TRB has fluctuated since 2000, increasing by CNY 14.02 billion, especially in the Hotan River region. Among the individual ecosystem services, the increase in regulatory services is the largest, rising to CNY 8.842 billion. The growth of ESV mostly occurred in the mountains and oases. (2) The rise in ESV is mainly due to the conversion of barren land to water and grassland; ESV loss is mainly affected by the conversion of water to cropland and barren land and grassland to cropland and barren land. (3) Human activity impact or intensity (HAI) is the key driving factor for the spatial stratified heterogeneity of ESV, followed by elevation (DEM). In the interaction analysis, HAI∩DEM interaction is the primary reason for ESV's spatial differentiation. The study's findings show that the combined effects of human activities, DEM, and hydrothermal conditions underlie the spatial stratified heterogeneity of ESV in the TRB. This conclusion provides a scientific basis for future ecological civilization construction planning.

Keywords: ecosystem service value; land use change; driving factors; Tarim River Basin

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1. Introduction

Ecosystem services (ES) are the basis for ecological protection, ecological function zoning, natural asset accounting and ecological compensation decisions. Ecosystem service functions show spatial and temporal dynamic changes that are closely related to ecological structure and ecological functions [1]. ESV is a quantitative estimation of ES capacity. The ESV in monetary form is to understand and apply for the general public and decision makers. It can contribute significantly to regional management, environmental control and ecological governance [2,3], making it widely used. The formulation of the Global ESV evaluation system in 1997 [4,5] has made ES research a hot spot in ecology.

Based on the classification of ES functions, Xie et al. [6] modified the global ESV evaluation system based on the actual situation of China's ecosystem and improved the ESV coefficients; a set of ESV coefficients has been established that can evaluate urban [7,8], island [9], and river basin [10,11] ecosystems. At present, this coefficient has been utilized in various ESV studies in China [12,13]. However, due to the obvious differences in regional ecosystem functions across the nation, this paper corrected the ESV coefficients with the help of the yield of food crops per unit area in the study region [14]. This adjustment will help us obtain the accounting results for the ESV that better fit the actual situation.

Climate change and the increasing intensity of social and economic activities have deepened the contradiction between human and ecological environment development [15–17]. Therefore, the quantitative assessment of ecosystem function changes and their driving mechanisms help to locate the root causes of ecosystem problems. Most research thus far has looked at driving mechanisms of ecosystem services as being mainly natural (biological), climate, soil, terrain and socioeconomic factors (land use, social and economic) [18]. Furthermore, most of the research in China and abroad has used correlation analysis [19], stepwise regression [20], the comprehensive evaluation model [21], and the geographically weighted regression model method [22] to determine and implement the influence factors. Another recent study employed the geographic detector and spatial analysis method, focusing on the interaction of influencing factors and the spatial variability of influencing effects. The impact of these influencing factors on the spatial heterogeneity of ecosystem service function regions was then analyzed [23,24].

The TRB is an extremely arid and ecologically fragile region [25,26]. The TRB has been substantially affected by global warming in recent years, resulting in grassland degradation, shrunken glaciers, dried up rivers, and creeping desertification. The warming has been exacerbated by the unreasonable allocation of water resources, including rapid changes in watershed land use patterns due to human activity [27,28]. These and other problems make the ecological environment of the watershed increasingly fragile, threatening the sustainable development of human society in the region. To ensure and promote the oasification of the region and coordinate and strengthen the bonds between "human-land, human-water, and human-natural environment", the government has carried out a large number of ecological protection measures that have achieved remarkable outcomes [29].

This paper explores the spatio-temporal variation characteristics of ESV in the TRB, based on long-term land use monitoring data. Furthermore, it quantitatively assesses the driving effects of both natural and socio-economic factors on ESV, using the resilience index and the geographic detector method. Additionally, the paper analyzes the characteristics of ES function changes in the basin, looking for the root causes of ecosystem problems and other related issues.

2. Materials and Methods

2.1. Study Area

The TRB is the largest inland river basin in China. It is situated north of the Kunlun Mountain in Xinjiang, northwest China (73°10′–94°05′E; 34°55′–43°08′N). The temperature stays between 9.1 °C and 11.1 °C all year round, and precipitation is in the range of 60–160 mm [30], giving the region a continental arid climate. Despite its extreme aridity and fragile ecological environment, the TRB is a key unit of China's efforts to build the Silk Road. Therefore, the economic development and ecological environment maintenance, not only of the basin but of the entire Xinjiang region, is critically important (Figure 1).

The surface rivers in the TRB are mainly distributed in a circular pattern in the basin's desert and oasis ecotone. Over the past few decades, both ecological and anthropogenic changes to the environment have led to perennial discontinuous flow in some of the region's tributaries. At present, only three tributaries in the upstream areas and one tributary in the Midlands have a surface water connection with the basin's main river [31]. The tributaries are the Aksu (AKS), Yarkand (YRQ), Hotan (HT), and Kaidu-Kongque (KK) rivers, and the main stream is the Tarim River (THGL).

2.2. Data Sources

Land use status data were derived from the annual China Land Cover Dataset released by Wuhan University. The data, which cover the TRB for the years 2000–2020, have a spatial resolution of 30 m and an overall classification accuracy of more than 80% [32]. According to the data requirements for calculating ESV in this paper, the dataset was reclassified into seven land use types: cropland, forest, grassland, water, built-up land, barren land, and wetland.

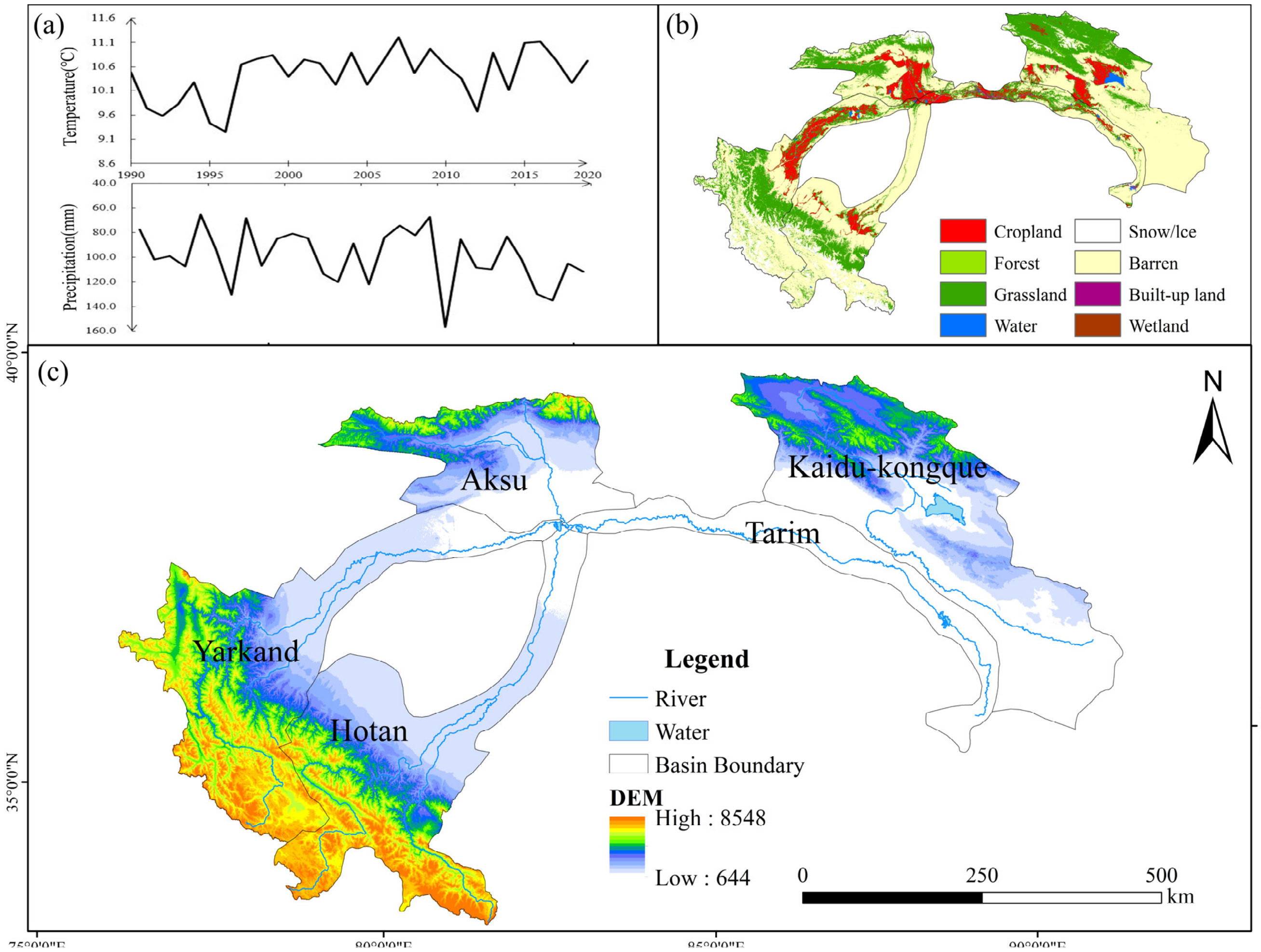

Figure 1. Overview map of the TRB (No. GS(2020)4619).(**a**) Changes in average annual temperature and precipitation in the TRB from 1990 to 2020; (**b**) Distribution of land use types in the TRB; (**c**) Topography and distribution of rivers in the TRB.

The climate and environmental monitoring data were provided by the National Heating Data Center, affiliated with the National Oceanic and Atmospheric Administration. According to our research needs, the spatial interpolation module of Arcgis10.2 was used to process the differences in the stations contained in the TRB. The terrain and slope data were obtained from the SRTM DEM data in the Geospatial Data Cloud, URL: http://www.gscloud.cn (accessed on 21 July 2022).

The socio-economic data mainly include population density data and GDP data, which are from the Resource and Environment Science and Data Center URL: http://www.resdc.cn (accessed on 5 August 2022), with a spatial resolution of 1 km.

2.3. Estimation of ESV

To facilitate our calculations, we classify hard-to-use land as barren, water and snow/ice as water, and construction land as cultural and entertainment ecological service functions [33]. The coefficient of the ESV was modified by the yield and value of crops per unit area in the study region's administrative unit. The correction method was calculated according to the formula based on the yield per unit area, sown area, and average price of each food crop [34], The ESV coefficient was corrected according to the crop yield and value per unit area of the administrative unit in which the study area is located, and the equivalent value factor of individual ES in the study area from 2000 to 2020 was 1881.82 Yuan·hm^{-2}, as follows:

$$E_a = \frac{1}{7}\sum_{i=1}^{n} \frac{m_i p_i q_i}{M} (i = 1, \ldots, n) \tag{1}$$

where E_a is the annual value of food crops in 1 hm^2 cropland (yuan ·hm^{-2}), while i is the crop type, the main crops in this area being wheat and maize. Furthermore, P_i is the national average value of food crops in i (yuan·kg^{-1}); q_i is the yield per unit area of i crop (kg·hm^{-2}); m_i is the area of i grain crops (hm^2); and M is the total area of n food crops (hm^2). Finally, 1/7 means that the value of ecosystem services per unit area is 1/7 of the output value per unit area of major food crops in the region for that year.

Based on the coefficient of the ESV for the TRB (Table 1), the ESV of the study area was calculated using the following formula [35]:

$$\begin{aligned} ESV &= \sum A_a \times VC_a \\ ESV_b &= \sum A_a \times VC_{ba} \end{aligned} \tag{2}$$

where ESV_b is the ESV in item b; A_a is the area of land-use type a in the study area; and VC_a is the coefficient of ESV of a land-use type. VC_{ba} represents the value of the b ecosystem services of the class a land-use type.

Table 1. ESV Coefficient for the Lower Reaches of the Tarim River/yuan·hm^{-2}.

Ecosystem Service Function	Land Use Type					
	Cultivated Land	Forest Land	Grass Land	Waters	Construction Land	Unused Land
Gas regulation	940.91	6586.37	1505.46	0.00	0.00	0.00
Climate regulation	1674.82	5080.92	1693.64	865.64	0.00	0.00
Water conservation	1129.09	6021.83	1505.46	38,351.50	0.00	56.45
Soil formation and protection	2747.46	7339.10	3669.55	18.82	0.00	37.64
Waste disposal	3086.19	2465.18	2465.18	34,211.50	0.00	18.82
Biodiversity conservation	1336.09	6134.74	2051.18	4685.73	0.00	639.82
Food production	1881.82	188.18	564.55	188.18	0.00	18.82
Raw material production	188.18	4892.73	94.09	18.82	0.00	0.00
Entertainment culture	18.82	2408.73	75.27	8167.10	82.60	18.82
Total	13,003.38	41,117.78	13,624.38	86,507.29	82.60	790.36

2.4. Human Activity Impact Analysis of ESV

The human activity impact or intensity (HAI) composite index can reflect the changes in LUCC and landscape formation in Xinjiang. On this basis, the HAI is used to evaluate the relationship between anthropogenic interference intensity and the ecological environment in Xinjiang [36,37]. The HAI formula can be written as follows:

$$HAI = \sum_{i=1}^{n} \frac{A_i P_i}{TA} \tag{3}$$

where HAI is the synthetic index of artificial intervention, A is the total area of the i-th landscape composition, P is the HAI parameter of the i-th landscape composition; TA is the total area of the regional landscape types, and n is the number of landscape compositions. According to the landscape type of the TRB, this paper uses the assignment method to determine the value of parameter P.

2.5. Land Use Change Elasticity of ESV

The elasticity method was used to measure the percentage change of ESV caused by LUCC, utilizing the following formula [38]:

$$E = \left| \frac{(ESV_{t_1} - ESV_{t_0})}{LUP} \right|, LUP = \frac{\sum_{i=1}^{n} \Delta L_i}{\sum_{i=1}^{n} L_i} \tag{4}$$

where E is the elasticity index, t_0 is the initial period of the study, t_1 is the end period of the study, LUP is the percentage of LUCC, ΔL_i is the LUCC area of i land-use types, and L_i is the total area of i land-use types.

2.6. Geographic Detector Model

The geographic detector model is a statistical method that detects spatial differentiation and explains its driving force [39]. Factor detection is used to find the spatial stratified heterogeneity of Y and to determine to what extent factor X explains the causes of the transformation of attribute Y.

When ESV spatial differentiation occurs, the interference of various influencing factors differs. There are complex interaction mechanisms among the influencing factors, so the interference ability, intensity, and direction of the influencing factors are different. The interaction mechanism between factors may affect their interference on the spatial differentiation of ESV [40]. Based on the relationship between the individual ESs in the TRB, eight driving factors of ESs in the study region were selected from the aspects of natural and social economy. The natural factors were as follows: X1: average annual temperature (TEM), X2: annual precipitation (PREC), X3: elevation (DEM), X4: slope aspect (SA) and X5: NDVI. The socio-economic factors include: X6: per capita GDP (GDP), X7: population density (PD) and X8: HAI.

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} \tag{5}$$

where h is the stratification/partitioning of variable Y or factor X; N and N_h are the number of cells in the whole region and h region, respectively; σ_h^2 and σ^2 are the variances of Y values in the whole region and h region, respectively.

Interaction detection primarily judges whether each factor has an independent influence on the dependent variable or an influence after interconnection, and whether the Interference capability is attenuated or strengthened [41]. There are five forms of association between the two factors (Table 2).

Table 2. Interaction Types.

Criterion Basis	Interaction
$q(X_1 \cap X_2) < \min[q(X_1), q(X_2)]$	Non-linear weakening
$\min[q(X_1), q(X_2)] < q(X_1 \cap X_2) < \max[q(X_1), q(X_2)]$	Single-factor non-linear attenuation
$q(X_1 \cap X_2) > \max[q(X_1), q(X_2)]$	Double factor enhancement
$q(X_1 \cap X_2) = q(X_1) + q(X_2)$	Independent
$q(X_1 \cap X_2) > q(X_1) + q(X_2)$	Non-linear enhancement

3. Results

3.1. Changes in the Watershed Ecological Service Value in the TRB

3.1.1. Time Variation Characteristics

This paper estimated the total ESV in the TRB from 2000 to 2020 (Table 3). The results show that the ESV rose from CNY 353.968 billion in 2000 to CNY 367.97 billion in 2020, for an overall increase in assets of CNY 14.02 billion. The Hotan River (HT) area exhibited the largest increase (CNY 8.832 billion). The Aksu (AKS) and Tarim rivers (THGL) charted the second largest growth rate, with an increase of about CNY 2.435 billion and 2.15 billion, respectively. Meanwhile, the Yarkand (YRQ) and Kaidu-Kongque rivers (KK) experienced relatively stable development, with both showing a modest growth trend of 111 million and CNY 474 million, respectively.

Regarding the value of single ES, regulation services accounted for the largest proportion and charted the most obvious growth trend. From 2000 to 2020, these services increased by CNY 8.842 billion. This was followed by support services, with an increase of CNY 2.97 billion, and supply services and cultural services with an increase of 1.809 billion and CNY 380 million, respectively.

Table 3. ESV in the TRB (CNY 100 million).

Basin Name	2000	2005	2010	2015	2020
YRQ	1126.41	1200.11	1237.85	1283.97	1127.52
AKS	520.86	507.98	598.04	551.21	545.21
THGL	212.74	232.90	223.78	223.43	234.24
KK	881.98	861.74	880.82	897.79	886.72
HT	797.69	873.42	898.60	900.81	886.02
Total	3539.68	3676.15	3839.09	3857.21	3679.71

Next, the growth trends of regulation services in HT, AKS and THGL in 2020 were compared with those in 2000 (Figure 2). The growth trend in HT was the most significant, representing a total increase of about CNY 6.645 billion over 20 years. In AKS, the growth trend showed an increase of about CNY 1.640 billion, while in THGL, the increase was CNY 1.596 billion. However, YRQ and KK showed a slight downward trend, decreasing by CNY 917 million and CNY 121 million, respectively.

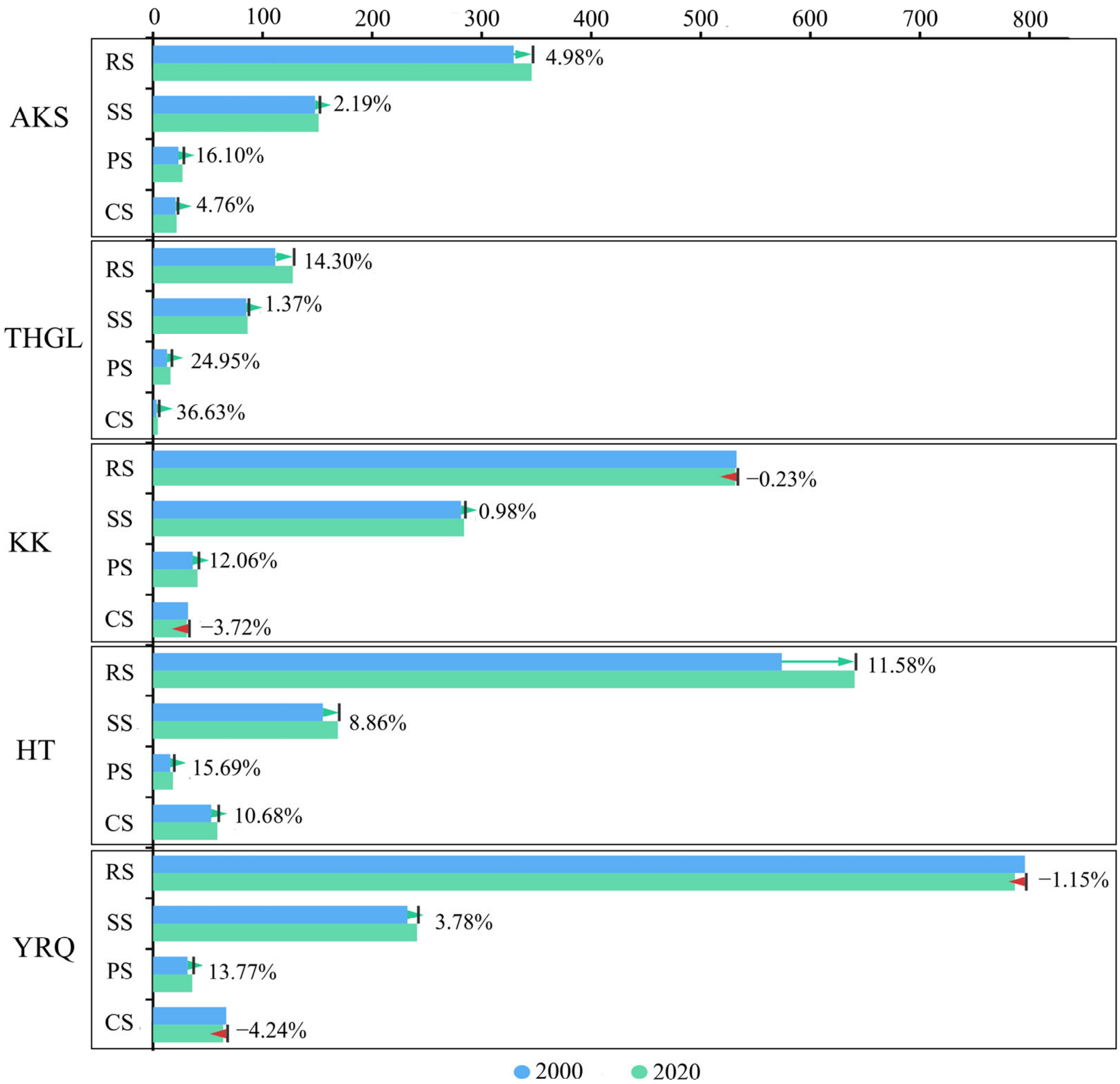

Figure 2. Variations in ESV for each sub-basin of the TRB (RS: Regulation Service; SS: Support Service; PS: Provision Service, CS: Cultural Service).

In each of the five sub-watershed areas, support services followed a clear growth trend from 2000 to 2020. HT rose the most, increasing by about CNY 1.374 billion, while AKS, YRQ, THGL and KK increased by CNY 324 million, 878 million, 117 million and 227 million, respectively. The changes in supply services were similar to those in support services for the same time frame, showing a growth trend. AKS, YRQ, THGL, KK and HT increased by CNY 373 million, 434 million, 319 million, 437 million and 246 million, respectively. However, cultural services had a slight downward trend in the KK region, decreasing by about CNY 119 million, while the other four regions showed a small upward trend.

In general, the ecological assets of the TRB were in a state of continuous accumulation during the period 2000–2020.Of these changes, the increase in regulatory services was the main reason for the appreciation of ecological assets, but support services, PS and CS also showed an upward trajectory.

3.1.2. Spatial Variation Characteristics

First, using the fishing net tool in ArcGIS 10.2, we divided the TRB into 40,922 grids [42]. Then we counted the ESV and spatially displayed the changes using the natural break point method (Figure 2). Five regional classes emerged, among which class 1 had the lowest ESV and class 5 had the highest.

As can be seen in Figure 3, the primary and secondary ESV regions are mainly distributed in the eastern part of KK, the central part of AKS, and the northern part of HT and YRQ. The landforms in these regions are mostly desert and Gobi, with low vegetation coverage and scarce water resources. Being affected by climate change and water resource allocation, the ESV in these regions also shows a decreasing trend. The tertiary areas of ESV are mainly located in the northwestern part of KK, the central part of THGL, HT, and the central and northern part of YRQ, which are dominated by oases and low mountains. The higher ESV in this region is mainly due to the higher vegetation cover and river distribution, and the agricultural development in the oasis area also supports the growth of ecological assets in this region.

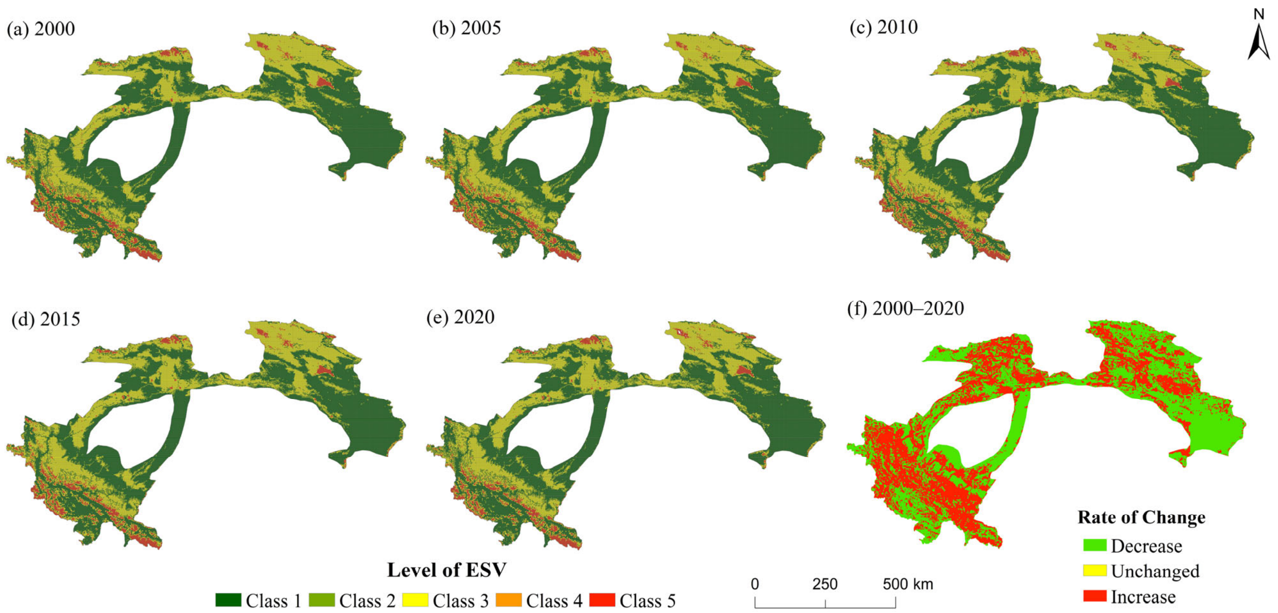

Figure 3. Changes in ESV distribution in the TRB during 2000–2020. (**a**–**e**) show the spatial distribution characteristics of ESV classes every five years, while (**f**) shows the change characteristics of ESV. (Class 1: CNY 0–4,135,360; Class 2: CNY 4,135,360.1–9,949,044; Class 3: CNY 9,949,044.1–24,183,096; Class 4: CNY 24,183,096.1–49,677,401; Class 5: CNY 49,677,401.1–91,347,521).

From 2000 to 2020, ESV class 3 areas changed significantly, as did ESV levels 4 and 5 areas, which are mostly distributed in the central and northwestern regions of KK, the northern regions of AKS, and the southern regions of HT and YRQ. The main geomorphic units in these areas are water, glacier and snow cover, so the primary reason for their high ESV value is abundant water resources and high vegetation coverage.

As shown in Figure 3f, the increased area of ESV in the TRB is mainly distributed in the oases and mountain region, while the decreased area of ESV is heavily located in the desert and Gobi region. There was also a decrease in the high mountains. In the whole TRB, the area covered by ESV as a growth trend is larger than that as a decrease trend. The ESV class 2 areas showed the biggest change, with the number of grids decreasing by 567 Until 2020, whereas the number of grids in ESV class 3 areas increased by 561. Meanwhile, the number of grids covered by ESV class 4 areas decreased, while those covered by ESV class 5 areas showed an increasing trend, adding 160 grids. The number of grids covered by ESV class 1 areas increased by 7, indicating no significant change.

In general, the spatial changes in ESV in the TRB mainly occur in oases and mountains. Specifically, the ESV in the AKS, the west of KK, and central YRQ and HT show a significant growth trend from 2000 to 2020. It can also be seen from the number of covered grids at all levels of ESV that the secondary ESV and tertiary ESV regions are the main change active regions, followed by the intensity of change in the quaternary ESV and tertiary ESV regions.

3.2. Interactions between Changes in Ecosystem Service Value and Land Use Change

3.2.1. Response of ESV to LUCC

This paper quantifies the ESV response to LUCC with the help of the elasticity index (Figure 4). During 2000–2020, the LUCC area of the TRB reached 32,152.66 km^2. The most drastic change occurred during 2005–2010, when nearly 10,111.95 km^2 was converted. Among the five sub-basins, the LUCC area of the YRQ region was the largest (12,356.57 km^2).

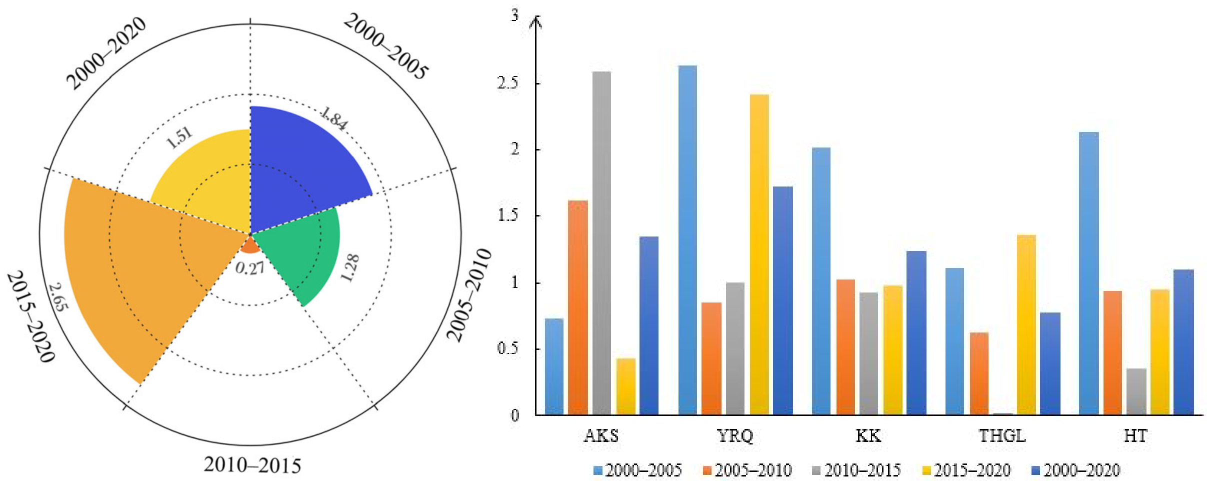

Figure 4. Average elasticity of ESV to LUCC in the TRB (the left figure is the average elasticity of the TRB, and the right figure is the average elasticity of each sub-basin).

The average elasticity of ESV in the TRB with respect to LUCC in 2000–2020 was 1.51. The highest was 2.65 in 2015–2020, 1.84 in 2000–2005, and 1.28 in 2005–2010. However, the elasticity decreased significantly to 0.27 in 2010–2015, indicating that land use change had a strong ability to interfere with ecosystem services during 2015–2020, 2000–2005 and 2005–2010. On the other hand, its ability to interfere decreased significantly in 2010–2015. This is most likely attributed to the gradual transformation of LUCC area of various ESV high-value land types from 2010 to 2015.

The biggest LUCC in 2010–2015 was barren land with low ESV, grassland, and water with high ESV, all of which decreased. The loss of ESV was, however, supplemented by the increase in arable land types with a higher unit area value. Therefore, the alteration in ESV due to overall LUCC conversions was small. In contrast, the LUCC from 2015 to 2020 was dramatic. Grassland and water showed a significant decline, transforming into barren and cropland, respectively. The transformation of ecological land to barren and cropland resulted in the complete deprivation of ecosystem functions in the TRB, resulting in a large change in the ESV, which is mirrored in the high elasticity index. Hence, the orderly distribution of water resources and scientific management of ecological land should be emphasized in the construction of ecological civilization in the TRB.

The average elasticity of ESV to LUCC in the YRQ during 2000–2020 is 1.72, while the average elasticity of AKS, KK, HT and THGL is 1.34, 1.23, 1.09 and 0.78, respectively. In order to study the change trend of the average elasticity of ESV to LUCC for each sub-watershed in different periods, we analyzed the average elasticity of the sub-watersheds. We found that YRQ had a strong disturbance ability of LUCC to ES function during 2000–2005 and 2015–2020. The change trend of the former is mainly a result of the substantial growth of ecological land, including woodland, grassland and water area, which showed a larger growth trend than in 2000. The water area showed the largest growth trend.

Climate change has increased snow and ice meltwater in the TRB. When the meltwater is combined with precipitation in the southern mountain region, the water and heat requirements necessary for the survival of natural plants in the area can be fully satisfied and the ecosystem service function can be strengthened. The significant causes of the change trend in this region are that the water area in 2020 showed a large decrease compared with that in 2015. Most of the lost water area was transformed into barren land, and the ecosystem service function was completely lost. Some of the water was converted into grassland and cropland, and the ecosystem service function declined. Compared with 2000–2005 and 2015–2020, the average elasticity values of AKS during 2005–2010 and 2010–2015 were higher, mainly because the areas of cropland, forestland, grassland and water with the strong ecosystem service capacity of AKS showed an increasing trend in 2010. Recent studies show that 2010 was a wet year in the TRB, giving the area abundant precipitation [43]. The special geographical location of AKS and the increase in glacier and snow meltwater led to the rapid growth of water area in 2005–2010. The area of grassland, forest and cropland also increased due to the increase in water resources. From 2010 to 2015, the decrease in precipitation, the reallocation of water resources, and the increase in water demand for agricultural development resulted in the continuous decline in water across the study region, resulting in a decline in the ESV.

The average elasticity of the KK and HT regions is similar to that of YRQ. In 2000–2005, the maximum average elasticity was 2.02 for KK and 2.14 for HT. Additionally, like YRQ, the increase in HT's average elasticity was mainly due to an expansion of water. The increase in the average elasticity of KK led to a reduction in water and grassland with high ecosystem service capacity, and this change was mainly caused by an amplification of cropland and barren areas. The middle and lower reaches of KK are densely packed with ecological land, resulting in the irrational deployment of water resources.

In the upper reaches of the TRB, grassland browning and thinning were caused by the intensification of human activities. The average elasticity of THGL from 2015 to 2020 was 1.35, which was mainly due to the fact that the water area of the region in 2020 showed a significant growth trend compared with that in 2015, while the barren area with weak ecosystem service ability showed a significant decreasing trend. This indicates that the ecological water transfer projects implemented in the lower parts of the TRB since 2000 have achieved obvious results, and the ecological environment of the TRB is now tending to a positive development trend.

Overall, the disturbance ability of LUCC to ESV in the TRB is mainly affected by water. The ecological land use in some areas is also affected by natural and human factors, as well as water resources stress. Therefore, maintaining the structural stability of land use types is a top priority in improving the ES function.

3.2.2. Impacts of Land Use Conversion on ESV in the TRB

In this paper, the LUCC transfer matrix is adopted to determine the mutual transformation relationship between different land types in the TRB from 2000 to 2020 (Table 4, Figures 5 and 6). The results show that the increase in ESV in the TRB was due to the conversion of barren land with weak ecosystem service function into ecological land, increasing the ESV by CNY 39.107 billion.

Table 4. LUCC Transfer Matrix of the TRB (km^2).

Land Use Type	CR	FO	GR	WA	BA	BL	WE	Total 2000
CR	17,943.94	5.81	1847.71	50.51	47.37	237.26	4.38	20,136.97
FO	106.66	609.07	0.86	1.55	0.00	0.67	0.13	718.94
GR	7545.51	254.92	83,202.14	248.81	7248.39	975.25	225.64	99,700.66
WA	127.40	4.43	274.09	16,392.81	2091.20	72.54	0.28	18,962.76
BA	2892.33	1.75	13,935.56	2475.82	191,888.74	415.79	0.06	211,610.05
BL	0.24	0	2.49	7.23	0.91	300.10	0.00	310.97
WE	22.44	2.17	26.93	1.29	0.01	0.00	310.64	363.48
Total 2020	28,638.53	878.14	99,289.79	19,178.02	201,276.62	2001.61	541.12	351,803.84

During the study period, 13,935.56 km^2 of barren land was converted to grassland, among which YRQ had the largest area (4017.74 km^2), HT had the second-largest area (3397.44 km^2), and AKS and THGL followed with 2198.79 km^2 and 2184.62 km^2, respectively. Meanwhile, KK's transformation area was the smallest (2136.95 km^2). The conversion of 2475.82 km^2 from a barren area to a water area mainly occurred in YRQ and HT, and the conversion area occupied 29.88% and 38.24% of the total conversion area, individually. From 2000 to 2020, 7248.39 km^2 and 2091.20 km^2 of grassland and water area were converted to barren land, respectively, and the ESV lost CNY 27.228 billion. The area of YRQ grassland converted to barren land was 1781.20 km^2, and the conversion area of KK (1548.87 km^2) was second only to YRQ. Overall, the modification area of AKS, HT and THGL accounted for 21.56%, 16.59% and 15.90% of the all transformed area, individually. The conversion of water to barren land mainly occurred in YRQ and KK, which converted 1026.63 km^2 and 546.67 km^2, respectively.

According to the comprehensive statistics of ESV increases in the conversion process of barren land, grassland and water area, the ESV rose by CNY 11.879 billion in total. From 2000 to 2020, the cropland area in the study area increased rapidly, mainly from grassland and barren land. The area of grassland converted into cropland was 7545.51 km^2, among which the conversion of YRQ was the most intense. THGL converted about 2107.02 km^2, while AKS and KK converted 1592.88 km^2 and 1513.34 km^2, respectively, and HT converted only 577.36 km^2. The area of barren land converted into cropland was 2892.33 km^2, which mainly occurred in KK, THGL and AKS, with conversion areas of 1033.97 km^2, 647.87 km^2 and 727.93 km^2, respectively. In the process of grassland conversion to arable land, ESV decreased by about CNY 469 million, while in the process of barren conversion to arable land, ESV increased by about CNY 3.532 billion.

In terms of spatial distribution, the modification of barren land to grassland mainly occurred in the middle of HT and YRQ and at the intersection of both tributaries with the AKS and THGL watersheds. There was also modification of barren to grassland in the middle of AKS and the middle and east of THGL. The conversion of barren land into water area took place in the southern high altitudes area of HT and YRQ, the northern part of AKS, the northern area of KK, and downstream THGL. Combining the spatial distribution characteristics of these two phenomena, it is clear that the increased glacial snowmelt and precipitation at high altitudes have contributed to the improvement in the ecological environment in the TRB sources. At the same time, the conversion of barren land into water in the downstream area of THGL expresses that the ecological water transfer project in this area was effective and the ES function in this area is strengthened.

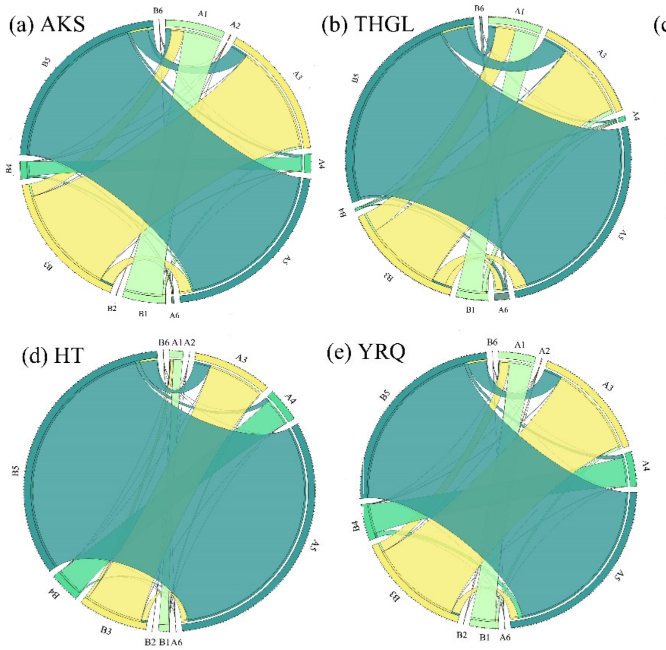

Figure 5. Current situation of land use transfer in the five sub-basins of the TRB (A1–A6: land use type area in 2020; B1–B7: LUCC types area in 2000; A1/B1: cropland(CR); A2/B2: Forest(FO); A3/B3: Grassland(GR); A4/B4: water(WA); A5/B5: Barren(BA), A6/B6: built-up land(BL); A7/B7: wetland(WE); Figure (**a**–**e**): land use transfer for each sub-basin in the study area).

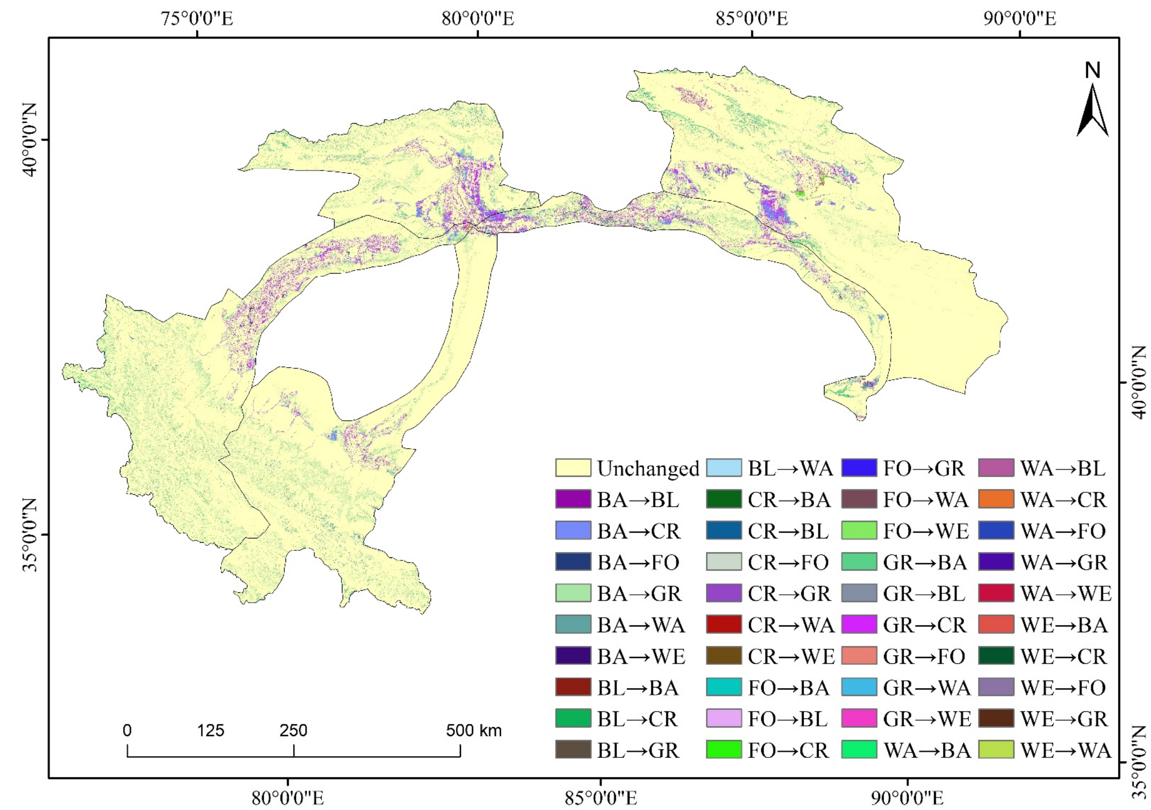

Figure 6. LUCC transfer in the TRB from 2000 to 2020 (CR: cropland; FO: forestland; GR: grassland; WA: water area; BA: barren; BL: construction land; WE: wetland).

However, with the melting of glacial snow due to climate change, the original snow-covered areas in the HT, YRQ and AKS are tending to brown out. As the modification of grassland to cropland intensifies in each sub-basin, mostly around the oasis and on both sides of the river, more and more water is consumed by agriculture. This consumption makes the ecological barriers around the oasis and on both sides of the river vulnerable to desert erosion, turning a terrific amount of grassland into barren land. The result is a loss in ecosystem service capacity, which then damages the ecological environment to some extent.

3.3. Driving Mechanisms of ESV Change

3.3.1. Detection and Analysis of Impact Factors

In this paper, the potential driving mechanisms of spatial stratified heterogeneity of ESV in the TRB from 2000 to 2020 were explored by using geographic detectors (Figure 7). Among the sub-basins studied, there are obvious differences in influence factors with regard to the spatial stratified heterogeneity of ESV. The driving factors for each sub-basin are ranked as follows: AKS (HAI > DEM > PREC > TEM > SA > PD > GDP > NDVI); THGL (HAI > DEM >PD > GDP > NDVI > TEM> PREC > SA); KK (HAI > DEM > TEM > PREC > NDVI > PD > GDP > SA); HT (HAI > DEM > TEM > NDVI > PREC > SA > GDP > PD); and YRQ (HAI > DEM > PREC > TEM> GDP > PD > SA > NDVI). The HAI is the main influencing factor in the spatial stratified heterogeneity of ESV in each sub-basin. The explanatory power of this factor is over 80% in AKS and THGL, over 60% in KK and HT, and over 40% in YRQ. The results show that the ecological service function is affected by the regulation and intensity of human activities, and is the decisive factor for the change in ecological assets in this area.

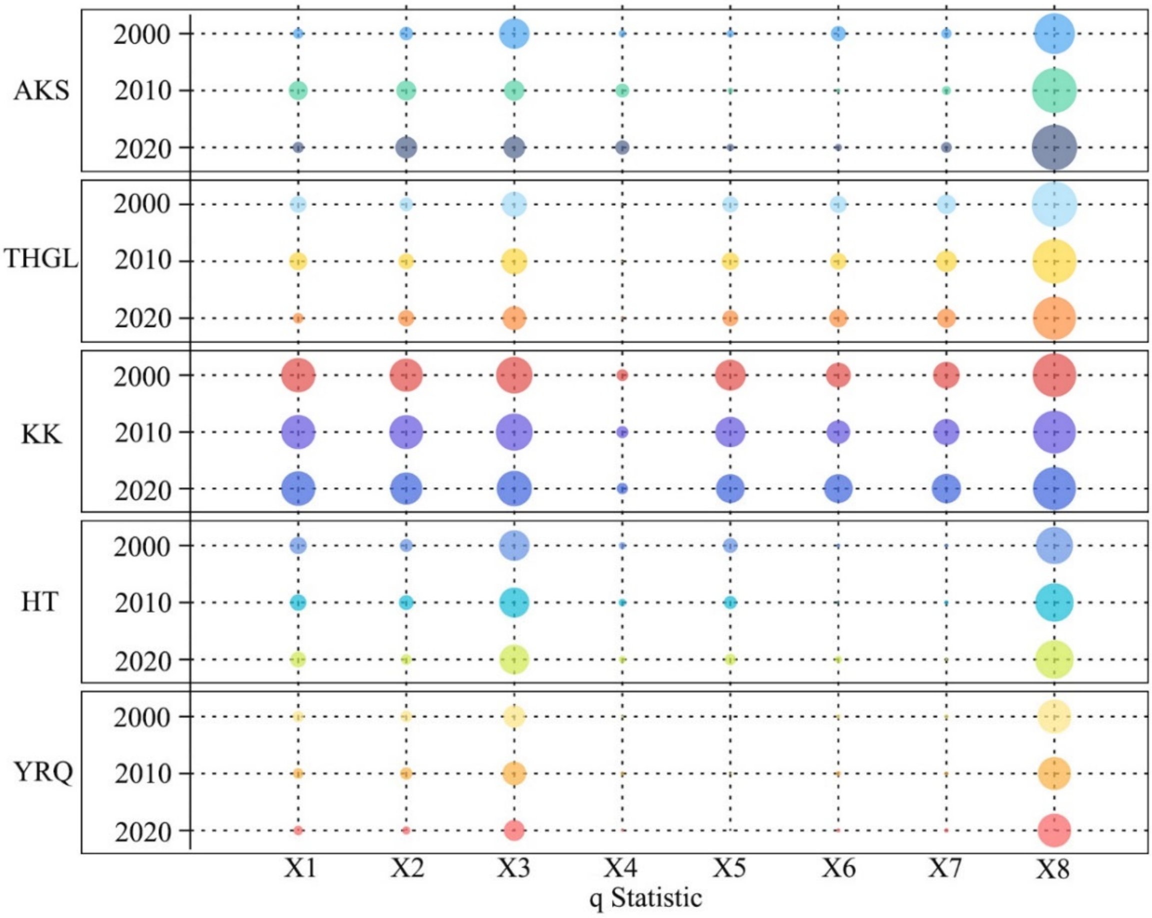

Figure 7. Factor detection of ESV spatial differentiation.

DEM, second only to HAI, is another key factor disturbing the spatial stratified heterogeneity of ESV in each sub-basin. Among them, AKS, KK and HT's PREC and TEM and NDVI have a greater influence on ESV differentiation, while PD, GDP and NDVI are potential factors for ESV differentiation in THGL. PREC and TEM are the main potential factors for ESV differentiation in YRQ, while PD, SA, and GDP have no significant impact on the spatial stratified heterogeneity of ESV in the sub-basins. Therefore, the spatial stratified heterogeneity in ESV in the TRB are primarily influenced by human activities and natural factors.

3.3.2. Analysis of Interaction Influence

When ESV spatial differentiation occurs, the interference of various influencing factors differs. There are complex interaction mechanisms among the influencing factors, so the interference ability, intensity, and direction of the influencing factors are different. The interaction mechanism between factors may affect their interference on the spatial differentiation of ESV [43]. Using eight different impact factors and interaction detection analysis, the results (Figure 8) show that the coupling modes between the independent factors mainly include non-linear enhancement effect and two-factors enhancement effect, and there is no mutually exclusive or attenuated connection. The strength of the mutual influence between factors of ESV spatial differentiation was significantly higher than that of the independent factor, which means that ESV spatial stratified heterogeneity in the TRB is the reason for the combined effects of multitudinous influencing factors. The higher q value of the interplay indicates that the interaction between two influencing factors has a greater ability to interfere with ESV spatial stratified heterogeneity in the TRB. In other words, the spatial stratified heterogeneity of ESV in the TRB is the reason for the variety of influencing factors. The larger the interplay q value, the stronger the interference ability of the interplay between the double impact factors on the spatial heterogeneity of ESV.

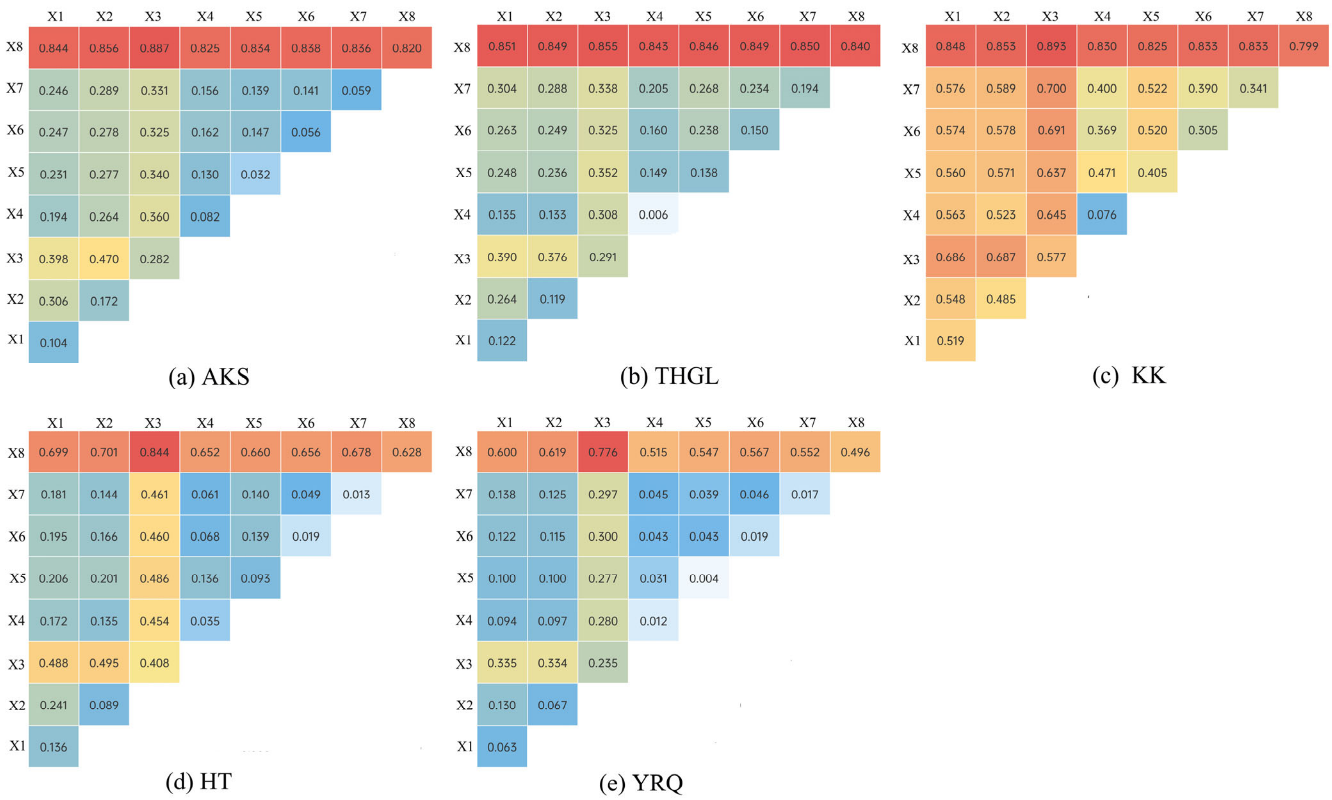

Figure 8. Factor interaction detection for ESV spatial differentiation. (figure (**a**–**e**): the two-factor interaction effects of each sub-basin in the study area; the color in the subplot tends to red for stronger correlation, and tends to blue for weaker correlation).

During 2000–2020, the interaction of HAI∩DEM (AKS: 0.887, THGL: 0.854, KK: 0.983, HT: 0.844, YRQ: 0.776) had the strongest influence on the heterogeneity of ESV. This is related to the high single-factor explanatory power of HAI and DEM in each sub-basin. The HAI∩TEM (AKS: 0.844, THGL: 0.850, KK: 0.848, HT: 0.670, YRQ: 0.600) and HAI∩PREC (AKS: 0.856, THGL: 0.849, KK: 0.852, HT: 0.700, YRQ: 0.619) were second only to HAI∩DEM in their spatial heterogeneity interference ability. By analyzing the interaction between natural factors, it can be seen that AKS, THGL, KK and HT DEM have the strongest interaction with PREC, followed by DEM and TEM. Furthermore, YRQ DEM has the strongest interaction with TEM, followed by DEM and PREC, while AKS and YRQ turn out to be nonlinear enhancement effects. THGL, KK and HT show a two-factor enhancement effect. Taking socio-economic factors as the starting point, HAI∩GDP (AKS, YRQ) and HAI∩PD (THGL, HT, KK) have the strongest interaction between factors, where AKS, THGL and KK show a momentous double factor heighten an effect, while HT and YRQ show a nonlinear enhancement effect.

Overall, the interaction of HAI with additional factors in the study area has a significantly stronger ability to interfere with ESV spatial stratified heterogeneity than that of individual factors. This is mainly due to the stronger ability of anthropogenic disturbance to interfere. Moreover, the spatial characteristics of the ecosystem service functions background of zonal geographic and climatic circumstances are intensely influenced by outside anthropogenic factors, which hugely enhances their spatial heterogeneity. The interaction between DEM and other natural factors also augmented hugely, signifying that the hydrothermal conditions and vegetation coverage in the TRB were greatly impacted by topographic conditions, which are important factors affecting ecosystem service functions. The synergistic effect of climate and socio-economic factors, such as TEM, PREC and DEM, improved the ecosystem service function, which was convenient to stabilize the ecosystem structure and rationally evaluate and improve the ecosystem service capacity. Therefore, the interaction of integrated impact factors should be considered.

4. Discussion

Ecosystem service value assessment transforms the current situation of the ecological environment into a quantity of ecological assets. Its intuitive form is more suitable for the interpretation of decision makers and the public, and it helps to discover problems. Overall, ESV assessment provides a scientific basis for promoting regional ecological civilization construction and optimizing management decisions.

Despite its obvious advantages, however, ESV evaluation can be contentious with regard to the various evaluation approaches. As more and more ecological indicators and remote sensing data are added to the evaluation systems along with regional characteristics, the accuracy and timeliness of ESV evaluation become increasingly convincing [44,45]. At present, the valuation of ES can be approximately discriminated into two types: a method based on unit service function price, and a method based on unit area value equivalent factor [46–48]. Of these two, the equivalent factor method is more intuitive, has a unified evaluation method and parameter standard, and is suitable for regional ecosystem service assessment [49]. Therefore, this paper adopted the revised value equivalent factor method, and integrated it with the features of the ecosystem in the TRB to make a more accurate assessment of the ESV.

Ecosystem services have significant spatial differentiation, which results from the coupling interaction between nature and socio-economic factors. Therefore, when exploring the influencing mechanism of ecosystem services, spatial differentiation should be paid attention to [50]. To delve into the mechanism affecting the study area's ecosystem services, this paper adopts a geographic detector model to conduct the influence mechanism study, which effectively combines the spatial factor data with the interaction between the two factors to meet the study and positioning of the ecosystem service driving mechanism at the spatial scale. However, the impact of local policy factors and human behavior to obtain economic value in the natural environment on ecosystem services is not yet fully understood. In follow-up work, more impact factors and other research methods should be comprehensively considered to evaluate the mechanism of ecosystem service change.

The TRB occupies a very significant position in the economic development of Northwest China, so ecological monitoring in this region is of extreme significance [51]. In this paper, four rivers in the basin that maintain surface water contact with the Tarim River were selected as the study area, mainly because the four sub-basins and the main stream basin are the main distribution areas of oases in the TRB, and the ecosystem distribution within the basin is relatively comprehensive. At present, the region is facing ecological problems such as desertification and salinization [52], which currently make up the central aspects of ecological environment recuperation in Xinjiang. Therefore, assessing the ecosystem services in this region and exploring their impact mechanism are conducive to discovering and locating ecological problems specific to the TRB. Targeted suggestions can then be put forward based on their occurrence mechanism.

During 2000–2020, the ESV of the TRB was on the rise, which primarily resulted in the process of converting barren land into water and grassland. According to the research results of influencing mechanisms, the major causes for the spatial changes in ESV in the region are human activities and DEM, followed by temperature and precipitation. From the perspective of anthropogenic disturbance, the total population of the TRB increased from 7,128,500 to 11,951,700 during 1990–2020. This represents an increase of 4,823,200 (67.66%) over the 1990 population [3]. The rise in population has increased the demand for agricultural land and agricultural water, so the cropland area in each sub-basin indicated a weighty growth trend during the study stage. A large amount of this cropland has been converted from grassland and water, while the expansion of agricultural land on both sides of the river has crowded the desert-oasis transition zone, destroyed the ecological barrier and led to land desertification. The result has been a decline in ecosystem service functions and a restriction of the sustainability of the ecological environment in the region.

The water area in the TRB showed an obvious growth trend during the research stage. The water of the main stream showed the most pronounced growth, accompanied by benign development of the natural environment in the downstream portion of the TRB. Prior to 2000, this region had a poor ecological environment, scarce land resources, declining groundwater reserves and dead vegetation due to human activities and climatic influences. However, since 2000, ecological water transportation projects have been started in this region, with 21 water transportations taking place by the end of 2020 [53,54].

The water and woodland area also presented a growth trend. In the context of climate change, there was a rapid increase in precipitation as well as runoff from glaciers and snow melt in the mountain area, greatly expanding the water [55]. The process of transforming barren land into water increased the ESV. Then, as the temperature gradually increased, mountainous areas transformed into barren land due to the decrease in glaciers and snow. This led to a decline in the ecosystem service function. The increase in temperature resulted in stronger evaporation, which is another reason for the decrease in water in some places. Therefore, human activities and social and economic development need to organically combine with sustainable development to stabilize and adjust the configuration of land and regional water resources allocation.

Rational exploitation and the use of regional ecological resources will require specific decisions in accordance with the different areas. By promoting the growth of ecosystem services and improving the basin's ecological dynamic mechanism, ecological protections can be strengthened at the same time as the social economy is rapidly developed, effectively enabling the construction of sustainable ecological civilization. To accomplish this aim, the coordinated symbiosis of regional ecological resources and ecological safety is very important.

5. Conclusions

Based on LUCC data in the TRB, this thesis estimated the spatial and temporal variability characteristics of ESV in the basin and selected a geographic detector model to detect the factors influencing the spatial heterogeneity of ESV occurrence. The following conclusions have been drawn.

(1) Between 1990 and 2020, the general ESV of the TRB showed a fluctuating growth trend, with an increase of CNY 14.02 billion. The HT district had the largest increase (CNY 8.832 billion), while regulation service was the largest single ecosystem function. The increase in ESV primarily emerged in the mountainous and oasis regions, with the AKS, western KK and central YRQ and HT exhibiting the most growth. The secondary and tertiary ESV regions were the main change areas during 2000–2020.
(2) HAI was the primary driving factor of ESV spatial heterogeneity in the study area, while DEM was secondary to HAI and a key factor in ESV spatial differentiation. In analyzing the interactions of influencing factors, we found that HAI∩DEM was the main reason for ESV spatial heterogeneity. The influence of HAI∩TEM and HAI∩PREC was lower than that of HAI∩DEM. Hence, the ecosystem services of the TRB during the study period were mostly affected by Artificial interference, climate, and topography.
(3) The transformation of barren land into water and grassland was responsible for the overall increase in ESV in the TRB over the past 20 years. On the other hand, the conversion of water area into cropland or barren land and the mutation of grassland into cropland or barren land were the driving forces behind the decrease in ESV in some areas. Therefore, the protection of ecological land, the optimal distribution of water resources, and the optimization of the relationship between ecological land and agricultural land are the key points that will result in successful and sustainable ecological civilization construction in the TRB.

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