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Original Articles

Interactions between ecosystem services and their causal relationships with driving factors: A case study of the Tarim River Basin, China

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A R T I C L E I N F O

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A B S T R A C T

Clarifying different ecosystem service (ES) interactions and their primary driving factors is essential for effective ecosystem management. Grassland degradation, interrupted river flow, and intensified human activities pose serious threats to the ESs of the Tarim River Basin (TRB). However, there is insufficient research on the between ES interactions and their causal relationships with drivers in the TRB. Therefore, this study measured four key ESs in the TRB: water yield (WY), carbon sequestration (CS), soil conservation (SC), and habitat quality (HQ). Correlation analysis and bivariate local spatial autocorrelation were employed to uncover trade-offs and synergies between different ESs from both holistic and spatial perspectives and ES bundles were identified using self-organizing maps. Geographic convergent cross-mapping was utilized to investigate the cause-and-effect relationships between ESs and their influences, pinpointing the main drivers. The findings revealed that: (1) from 2000 to 2020, WY and SC decreased, whereas CS increased markedly. HQ initially declined but then improved, with an overall insignificant change. Spatially, low-value ES regions were in the central and eastern desert areas, high WY and SC values occurred in mountainous regions, and high CS and HQ values were found in oases and mountainous areas; (2) ESs exhibited significant synergy throughout the watershed. Spatially, trade-offs and synergies coexisted, with high-high synergy predominating in mountainous regions and low-low synergy occurring primarily in the central and eastern desert areas. Trade-off effects were limited, mainly occurring in oases and parts of the Kunlun Mountains. ES bundles exhibited signs of change or deterioration, and the CS regulation bundle and WY supply bundle in particular face degradation risks; (3) the dominant direction of bidirectional asymmetric causality differed across ESs and drivers. Overall, the dominant direction of WY and drivers was that WY influenced drivers (WY → drivers), whereas SC was typically influenced by drivers (drivers → SC). The dominant orientation of CS and HQ concerning drivers is that natural factors influenced these ESs (natural factors → ESs), while human factors were influenced by ESs (ESs → human factors). The main drivers for WY and SC were precipitation, temperature, potential evapotranspiration, and elevation. The main drivers for CS and HQ were land use intensity, followed by precipitation, potential evapotranspiration, and temperature. The results of this study provide a reference for the conservation and management of ESs in the TRB.

1. Introduction

Ecosystems offer diverse services, known as ecosystem services (ESs) (Costanza et al., 2017), that are essential for human survival and progress. ESs are closely linked to regional ecological security and affect human well-being. However, the growing threats of climate change and escalating human activities are exacerbating the deterioration of these ecosystem functions (Luo et al., 2024). Research has indicated that changes in land use significantly disrupt ecosystem structures and ESs, leading to ecosystem and decreased benefits for people (Mao et al., 2019; Sannigrahi et al., 2020). Thus, in the context of the increasing degradation of ESs, clarifying the spatial heterogeneity, interactions, and drivers of ESs is a crucial precondition for promoting sustainable regional development.

Investigating the relationships among ESs is necessary for effective ecosystem management (Gao and Zuo, 2021). The interactions among ESs involve trade-offs/synergies and bundles (Shen et al., 2021). These relationships are typically dynamic due to the spatiotemporal

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heterogeneity and drivers of ESs. When a change in one ES affects the increase or decrease of other ESs, synergy or a trade-off between ESs occurs (Bennett et al., 2009; Spake et al., 2017). Currently, correlation analyses are frequently utilized to gauge trade-offs/synergies in ESs (Gou et al., 2021). However, this approach has a limited ability to characterize trade-offs/synergies in spatial relationships and can only focus on overall trade-offs/synergies. Therefore, some scholars have combined correlation analyses and bivariate local spatial autocorrelation (Ren et al., 2024) to analyze trade-offs/synergies based on the correlation analysis, which is more conducive to understanding the trade-offs/synergies of ESs both holistically and locally (Liu et al., 2024). The trade-offs and synergies of ESs are spatially formed into bundles, termed ES bundles (ESBs) (Xu et al., 2021). Identifying ESBs can enhance the understanding of the spatial relationships within ESs and facilitate the spatial management of ESs. Currently, the most popular methods employed to recognize ESBs are K-means clustering (Dong et al., 2023) and self-organizing maps (SOMs) (Dittrich et al., 2017; Dou et al., 2020; Xia et al., 2023). SOMs have been widely applied due to their excellent fault tolerance and interpretability (Dittrich et al., 2017).

In addition to increasing the understanding of ES interactions, investigating the causal links between influencing factors and ESs is crucial for effective spatial management (Dade et al., 2019; Liao et al., 2021). Ecosystems are impacted either directly or indirectly by complex natural circumstances and human activity (Liu et al., 2021). Climate has the most obvious impact on ecosystems (Shi et al., 2021), affecting the supply of ESs by altering their structure and functioning (Fang et al., 2021). In turn, ecosystem patterns may affect the local climate through altering biogeochemical cycles, thereby impacting human well-being. Research has indicated a shift in the primary drivers of ES from natural factors to human activities over time (Kang et al., 2023). Human-induced land change has been identified as the primary direct factor influencing ecosystems (Wu et al., 2022). Currently, the approaches used to investigate the driving factors of ESs are the geographical detector (An et al., 2023; Wang et al., 2023), geographical weighted regression (Yang et al., 2021), and structural equation modeling (Hu et al., 2023; Jiang et al., 2023). However, these methods only assess how drivers affect ESs unidirectionally, without accounting for the bidirectional causality between drivers and ESs. Although convergent cross-mapping has been employed to determine causality in multiple disciplines (Sugihara et al., 2012), this model is not suitable for studying causality in spatial data (Gao et al., 2023). Gao et al. (2023) introduced geographic convergent cross-mapping (GCCM), which integrates generalized embedding theory and dynamical system theory, building upon the foundation of convergent cross-mapping. The GCCM approach can utilize spatial cross-sectional data to identify bidirectional asymmetric causation ignored by linear models, and the output is more robust than that of linear models. Therefore, this study adopted GCCM to reveal the causality of ESs and pinpoint critical ESs. Studying the causality of ESs and drivers can effectively explain interactions between nature, society, and ecosystems.

The Tarim River Basin (TRB) is a significant resource supply region located in northwestern China. Its unique climatic and geographic conditions have created important resources such as water, biodiversity, and oasis land in the arid zone, which are essential for sustaining ecological equilibrium. The TRB's unique mountain–oasis–desert ecosystem has long provided important regional ESs such as water circulation, climate regulation, carbon sequestration, and biodiversity, which are important for maintaining regional ecological stability (Liu et al., 2022). The TRB's delicate ecology renders its natural systems particularly susceptible to anthropogenic impacts and climatic variations. In recent years, the TRB has experienced the impacts of climate change, manifesting as grassland degradation, glacier reduction, and the interruption of the river flow (Zhang et al., 2023). Combined with anthropogenic impacts, these conditions have placed several ESs at risk of degradation and have posed a significant challenge to sustainable regional development (Xue et al., 2019). As a result, there is an urgent need to investigate the ESs of the TRB and their driving mechanisms. The present study selected the TRB as the study area and assessed the water yield (WY), carbon sequestration (CS), soil conservation (SC), and habitat quality (HQ) using InVEST. Then, considering that the overall and spatially localized relationships of ES interactions in the TRB are still unclear, this study investigated the overall and local trade-offs/synergies between different ESs using correlation analysis and bivariate local spatial autocorrelation, respectively. SOMs were then employed to determine the ESBs. Finally, GCCM was utilized to examine the causality of the ESs and ES drivers. This study aimed to: (1) discover spatiotemporal heterogeneity in ESs; (2) reveal the complex relationship between ESs; and (3) reveal the causality between ESs and drivers and identify key ES drivers. The results can provide references and recommendations for the protection and management of ESs on the TRB.

2. Materials and methods

2.1. Study area

The TRB (73°10′–94°05′E, 34°55′–43°08′N) is the largest inland river basin in China (Fig. 1). The research region is 1.03 million km^2 in size and has an elevation of 768–7249 m. The Tarim River originates in the Tianshan and Karakoram mountains (Fan et al., 2013), with precipitation and glacial meltwater from the alpine mountains providing the primary sources of recharge. The river spans 1321 km in its entirety (Ling et al., 2020), and eventually dissipates in deserts and oases. Historically, the Tarim River was recharged by nine rivers. However, due to climate change and anthropogenic intervention, at present, the Tarim River is only recharged by the Aksu, Hotan, Yarkand, and Kaidu-Kongqi rivers (Xu et al., 2010). The TRB is a typical ecologically fragile area with a continental arid climate that is abundant in light and heat resources, with a mean annual temperature of 10.6–11.5 °C, annual evaporation of 800–2200 mm, and annual precipitation of about 120 mm (Ling et al., 2019; Zhou et al., 2022). The Taklamakan Desert is located in the central TRB and is extremely vulnerable to climate fluctuations due to its surroundings of oases, the Gobi Desert, and foothills (Chen and Xu, 2005). With the increasing severity of land degradation, water shortage, and ecological fragility, the ecosystem of the TRB faces major challenges (Kulaixi et al., 2023). Notably, the growth of the human population and agriculture has placed additional strain on environmental resources and accelerated the deterioration of natural ecosystems (Feng et al., 2022).

2.2. Data sources

As shown in Table 1, the data used in this study including land use/cover (LULC), precipitation (PRE), temperature (TEM), potential evapotranspiration (PET), soil data (HWSD), digital elevation model (DEM), normalized difference vegetation index (NDVI), spatial distribution of population (POP) and gross domestic product (GDP) data from 2000 to 2020. The data on actual water production were derived from the Xinjiang Uygur Autonomous Region Water Resources Bulletin. Missing GDP data for 2020 were replaced with 2019 data. The relevant data were synthesized into yearly data based on monthly scales. Data on the soil type/content, soil depth, and other data were extracted according to the HWSD. The slope data were obtained from DEM data. The annual NDVI data were processed using the MODIS processing tool (MRT) and finally obtained using the maximum synthesis method. All data coordinate systems were unified as WGS_1984_Albers.

2.3. Research framework

The workflow of this study followed the order of "ES quantification–ES interactions–ESs and driver causality − spatial management recommendations." The specific framework of the research is depicted in Fig. 2.

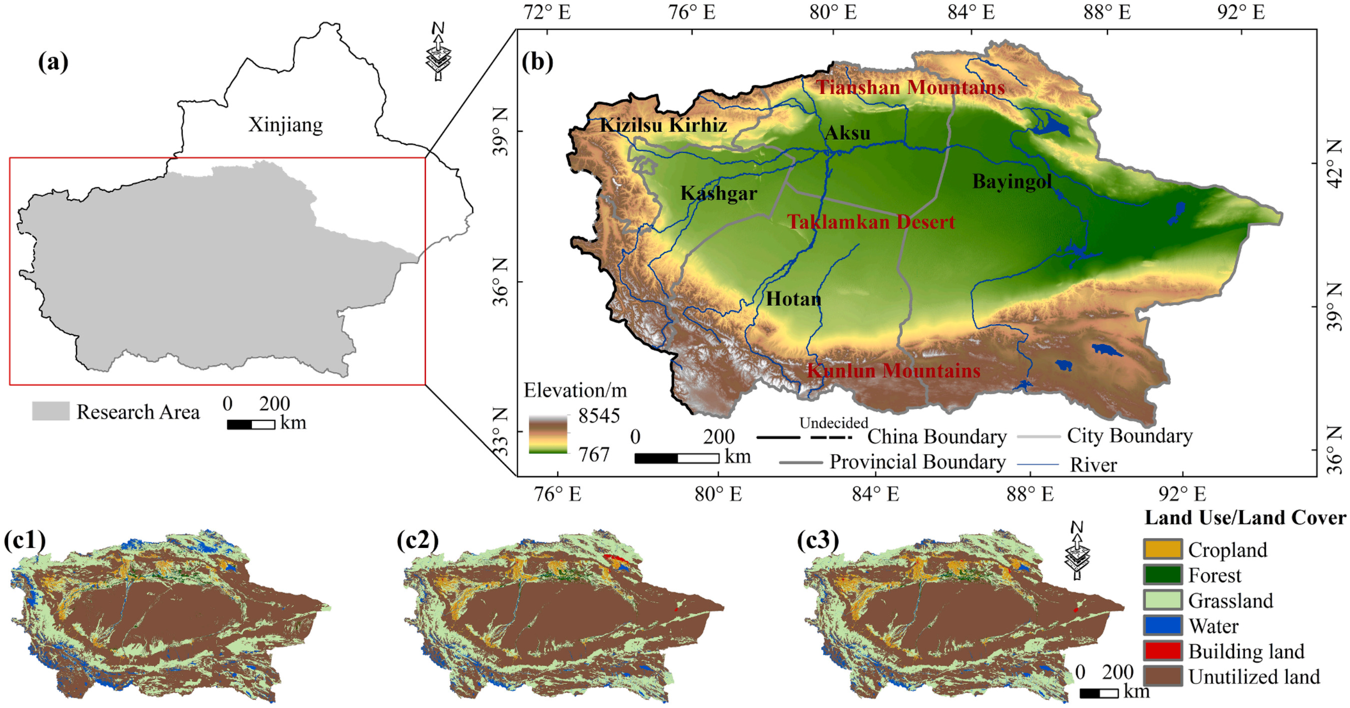

Fig. 1. Research area. (a) Location of the TRB; (b) elevation and regional profile of the TRB; (c1), (c2), and (c3) indicate the land use/land cover of the TRB in 2000, 2010, and 2020, respectively. Map inspection number: GS (2023)2767.

Table 1
Datasets and sources.

Data name	Resolution	Source
LULC	30 *m* Annual	Resource and Environment Science and Data Center, Chinese Academy of Sciences (https://www.resdc.cn/)
PRE	1000 *m* Monthly	Science Data Bank (https://www.scidb.cn/)
TEM	1000 *m* Monthly	National Tibetan Plateau / Third Pole Environment Data Center (https://data.tpdc.ac.cn)
PET	1000 *m* Monthly	National Earth System Science Data Center (https://www.geodata.cn)
NDVI	500 *m* 16-Day	National Aeronautics and Space Administration (https://search.earthdata.nasa.gov/)
POP	30 Arcsec Annual	Oak Ridge National Laboratory (https://landscan.ornl.gov)
GDP	1000 *m* Annual	Resource and Environment Science and Data Center, Chinese Academy of Sciences (https://www.resdc.cn/)
Soil Data	1000 *m*	Harmonized World Soil Database (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/)
DEM	90 *m*	Geospatial Data Cloud (https://www.gscloud.cn/)

2.4. Methods

2.4.1. Quantification of ESs

Considering how the TRB is currently developing both socially and ecologically, this study selected four typical ESs for analysis in terms of provisioning, supporting, and regulating services: WY, CS, SC, and HQ. These four crucial functions are critical for maintaining biodiversity and improving human well-being (Xu et al., 2022). InVEST was employed to quantify the four ESs. The methodology and specific parameters used to quantify each ES are shown in Appendix A1. Considering the workload and precision of the study, ESs were unified at a resolution of 6 km. Subsequent studies have been conducted at this scale.

2.4.2. ES trade-off/synergy assessment

The Spearman correlation coefficient is a simple and effective method to measure the relationship between ESs that has been extensively employed in research on the trade-offs/synergies between ESs. Therefore, this study measured the trade-offs/synergies between the four types of ESs using the Spearman correlation coefficient. The formula is as follows (Li et al., 2024):

$$R_{XY} = 1 - \frac{6\sum_{i=1}^{n}(X_i - Y_i)^2}{n(n^2 - 1)} \quad (1)$$

where R_{XY} is the correlation coefficient between X and Y; X_i and Y_i are the i sample values of X and Y, respectively; and n is the number of samples. $R > 0$ indicates a synergistic relationship between the ESs, $R < 0$ indicates a trade-off between the ESs, and an R value that is insignificant or tends to be 0, indicates that the ESs are not correlated.

Correlation analysis reflects only the overall trade-offs/synergies between ESs, without analyzing the spatial heterogeneity of trade-offs/synergies (Dong et al., 2023). Researchers commonly employ bivariate local spatial autocorrelation to investigate the spatial variations of trade-offs and synergies in ESs. This method is utilized to analyze the relationship between two variables within specific spatial units. Therefore, the bivariate local spatial autocorrelation in the GeoDa software can reflect the spatial heterogeneity of trade-offs/synergies. The formula is as follows (Wang et al., 2021):

$$I_{ij} = \frac{X_{ai} - \overline{X}_a}{\sigma_a}\sum_{j=1}^{n}\left(w_{ij}\frac{X_{bj} - \overline{X}_b}{\sigma_b}\right) \quad (2)$$

where I_{ij} is the bivariate local spatial autocorrelation coefficient; X_{ai} is the value of a in the spatial unit i; X_{bj} is the value of b in the spatial unit j; $\overline{X}_a$ and $\overline{X}_b$ are the mean values of a and b, respectively; σ_a and σ_b are the standard deviations of a and b, respectively; n is the number of spatial units; and w_{ij} is the spatial weight matrix. The spatial units of ESs were categorized into four clusters based on their clustering characteristics: high-high (H-H) synergistic, low-low (L-L) synergistic, high-low (H-L) trade-off, and low–high (L-H) trade-off ($p < 0.05$). Among these clusters, H-H and L-L indicate that a geographic unit and neighboring

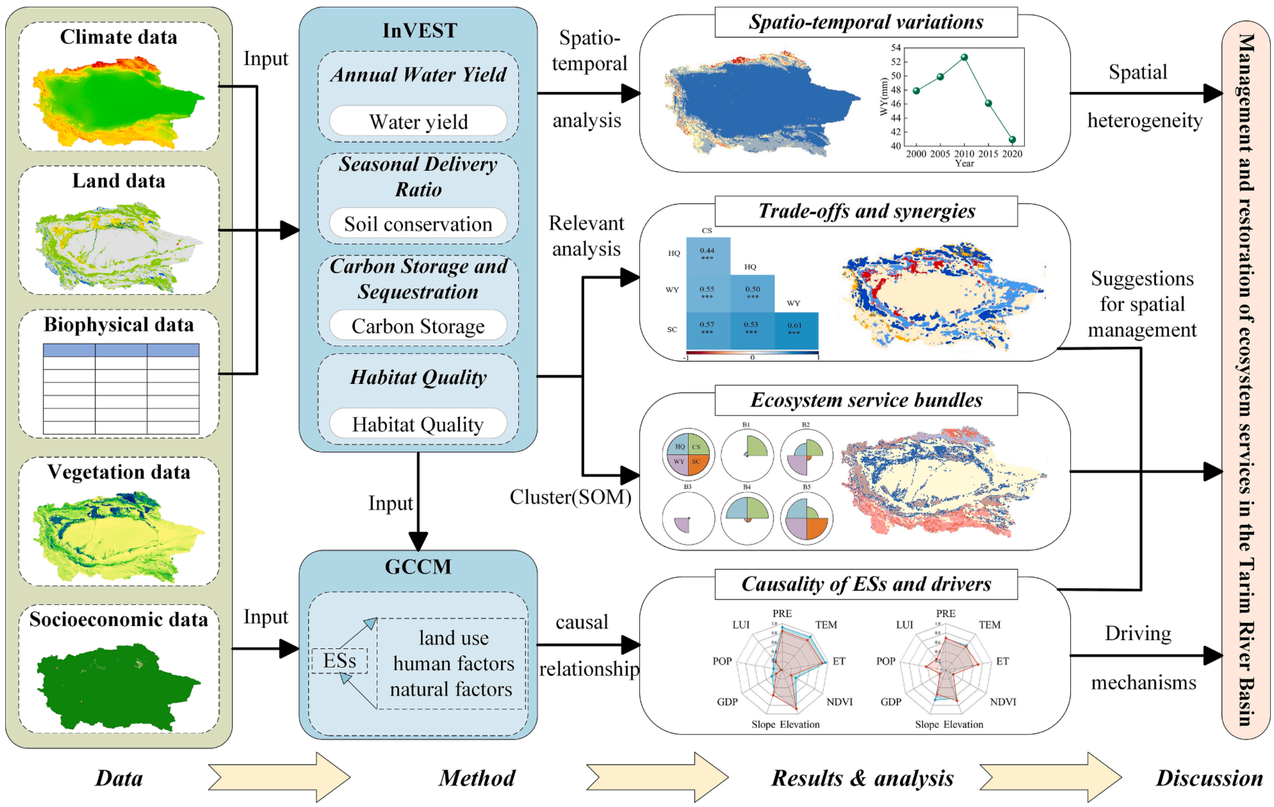

Fig. 2. Research framework.

units exhibit either high or low values for both variables, respectively, showing positive spatial autocorrelation. H-L and L-H indicate that a high or low value for one variable is spatially adjacent to a low or high value for another variable, respectively, showing negative spatial autocorrelation.

2.4.3. Identification of ESBs

The SOM is an unsupervised learning neural network algorithm that is widely applied to the clustering analysis of multidimensional data. The SOM can categorize grids with high similarity into the same ESB according to spatial co-occurrence in ESs (Shen et al., 2020). Therefore, this study used the "kohonen" package in the R software to implement the SOM. To achieve the cross-temporal comparability of ESBs, the ESs were standardized.

2.4.4. Causality of ESs and drivers

Based on the regional conditions and ES characteristics of the TRB, the selected drivers included both natural and anthropogenic factors (Fig. S1). Natural factors included six indicators, PET, PRE, TEM, NDVI, Elevation, and Slope, which can reflect the influence of climate, vegetation, and topography on ESs. The selected anthropogenic factors included the GDP, POP, and land use intensity (LUI) index, which can directly reflect the impacts of economic development, the population agglomeration level, and land use status on ESs, respectively.

The GCCM method is used for causal inference between two variables in space, which is conducive to identifying the dominant direction of bidirectional asymmetric relationships and overcoming the mirror effect (Gao et al., 2023). Therefore, GCCM was selected to analyze the bidirectional asymmetric causality of ESs and drivers in this study. GCCM was implemented in R software. Because there was a clear linear correlation between ESs and drivers, linear trends were removed using linear regression before GCCM was performed. The coordinates of each raster were utilized as independent variables, while the ESs and drivers were set as dependent variables. The residuals were obtained by subtracting the dependent variables from the fitting values. Finally, the residual and the corresponding spatial grid were used as the input for GCCM.

3. Results

3.1. Spatiotemporal variations of ESs

The spatial distributions of the four ESs exhibited evident heterogeneity inside the TRB, with each ES showing a relatively stable distribution pattern. (Fig. 3). Specifically, the northern and southern mountainous regions exhibited higher WY values, whereas the central Taklamakan Desert exhibited lower WY values. High WY values were centered in the water-producing area, which features rich precipitation, high grass cover, and low water consumption. Conversely, WY values were low in the plain runoff dissipation area, which experiences low precipitation and high water consumption. The distribution pattern of SC closely resembled that of WY, with high SC values concentrated in mountainous and southern premontane areas. These regions have strong soil and water conservation due to their high vegetation cover. High CS were primarily situated in oases and mountainous regions, which are characterized by mountains, river valleys, and oases with a high degree of vegetation cover, which collectively contributes to a high carbon storage capacity. Low CS values were mainly found in deserts and the Gobi, which have sparse vegetation. High HQ values were primarily found in mountainous and oasis regions. Between 2000 and 2020, the area with high HQ values significantly decreased in the oasis region, while it increased in the Kunlun Mountains. Low HQ areas were predominantly located in the central and eastern desert regions.

Temporal changes in ESs were analyzed by examining the annual average value of each service (Fig. 4). Different trends were observed for each ecosystem service between 2000 and 2020, with notable disparities in trends before and after 2010. Specifically, WY and SC exhibited similar patterns, with an upward trend before 2010 followed by a

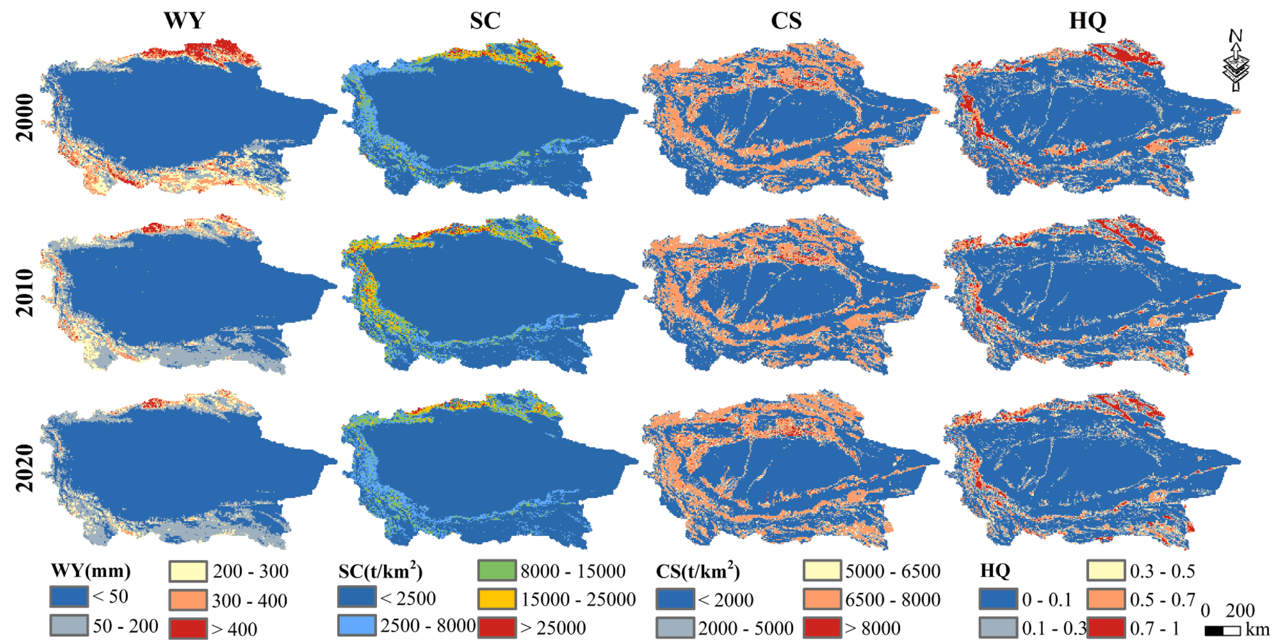

Fig. 3. Spatiotemporal patterns of ESs in the TRB.

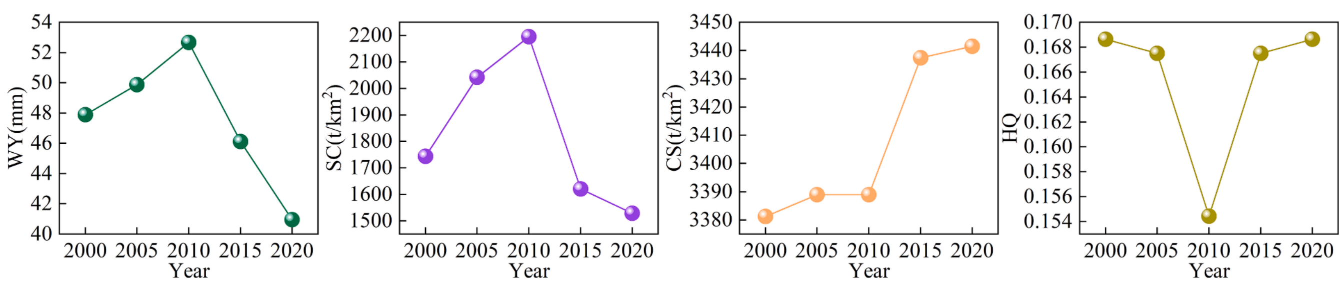

Fig. 4. Temporal changes in the mean values of ESs.

downward trend after 2010. The overall decreasing trends over the study period for WY and SC were 6.92 mm and 215.38 t/km^2, respectively. In contrast, CS demonstrated a consistent upward trend, exhibiting the most significant increase after 2010, with a rise of 60.20 t/km^2 over the study period. Despite considerable fluctuations, the HQ in 2020 was not much different from that in 2000.

3.2. Trade-offs and synergies between ESs

Correlation analyses were conducted on four ESs in the TRB to understand the trade-offs/synergistic relationships among them. This research identified six ES relationships, all of which exhibited synergistic relationships ($p < 0.001$) (Fig. 5). The highest synergistic effect was observed in WY-SC, while the lowest was obtained for CS-HQ. The synergistic relationships between CS-HQ, CS-WY, and CS-SC showed a trend of decreasing and then increasing over time, WY-SC showed an increasing trend, and HQ-WY and HQ-SC remained stable. In 2010, WY and SC increased significantly in the western region, with a decline in HQ in the oasis zone in the Tarim Basin. However, these trends were not observed in CS, which resulted in the weakening of the synergy between CS-HQ, CS-WY, and CS-SC during the year.

The results of the bivariate localized spatial autocorrelation reflected significant spatial heterogeneity in the trade-offs/synergies between ES pairs (Fig. 6). Synergistic effects dominated the ES pairs, with H-H

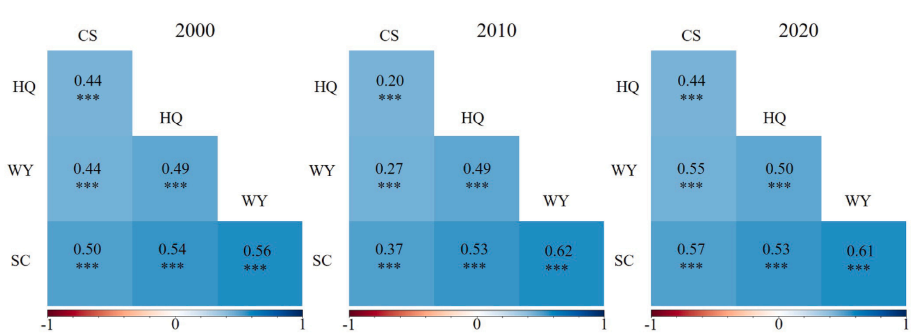

Fig. 5. Analysis of the correlations between ESs. Note: *** means $p < 0.001$.

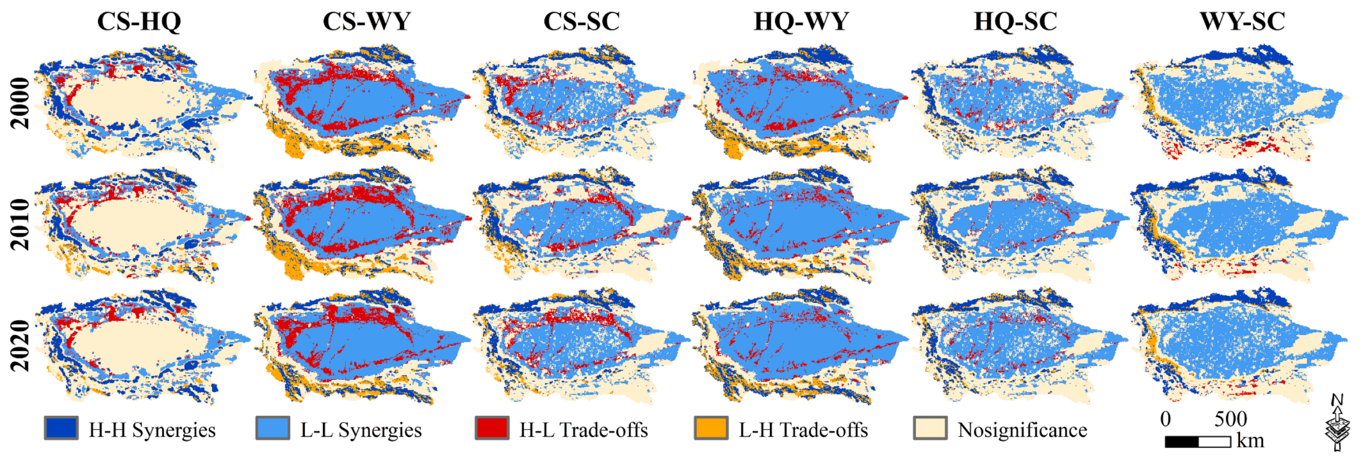

Fig. 6. Spatial distribution of trade-offs/synergies between ES pairs. Note: H-H denotes the clustering of X high-value ES and Y high-value ES for X-Y; L-L denotes the clustering of X low-value ES and Y low-value ES; H-L denotes the clustering of X high-value ES and Y low-value ES; and L-H denotes the clustering of X low-value ES and Y high-value ES.

synergism primarily found in mountainous areas with higher ESs, and L-L synergistic effects mainly concentrated in the Taklamakan Desert, which had lower ESs. Trade-off effects were less common and were mainly observed in oasis zones and mountains. Specifically, the CS-WY, CS-SC, HQ-WY, and HQ-SC ES pairs exhibited H-L trade-offs mainly in the oasis area, while the L-H trade-offs were mainly found in the southern and western mountainous regions. The H-L trade-offs of CS-HQ were predominantly located in the northern mountainous area, with L-H trade-offs sporadically distributed in the southern mountainous areas. There were fewer WY-SC trade-off effects, with H-L trade-offs patchily distributed in the southern mountains and L-H trade-offs concentrated in the western mountains.

This study examined area changes in ES pairs to further understand the trade-offs/synergistic changes among ESs (Fig. 7). Overall, there was a tendency toward stabilization in the regional ecosystem as indicated by the growing trend in the area percentage of the synergistic impact for each ES pair coupled with the less noticeable variations in the area proportion of the trade-off effect. HQ-WY, CS-WY, and WY-SC exhibited the largest increases in the area of synergistic effects, with increments of 7.00 %, 6.41 %, and 6.00 %, respectively. Conversely, HQ-WY and CS-WY experienced the largest decreases in the area of trade-off effects, with decreases of 3.73 % and 3.12 %, respectively. From 2000 to 2010, the trade-off area of CS-HQ, CS-WY, and CS-SC expanded, while the synergistic area decreased, further explaining the overall decline of synergistic relationships among CS-HQ, CS-WY, and CS-SC in 2010.

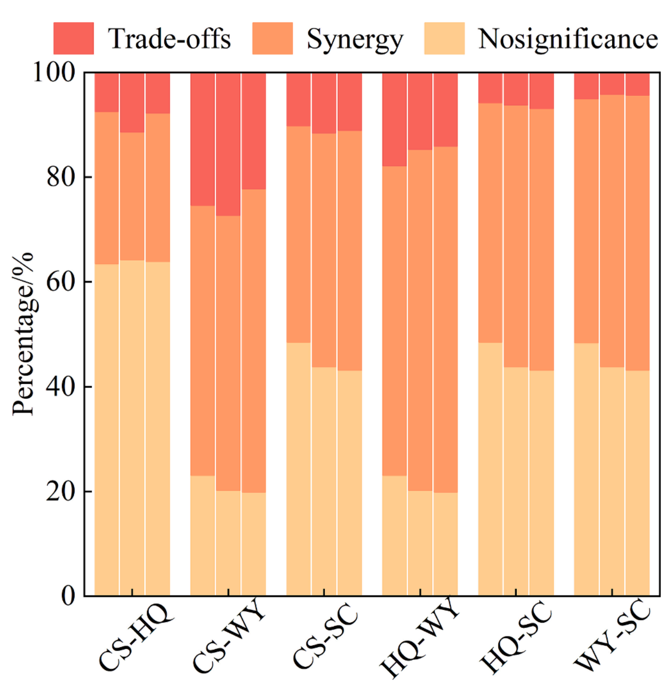

Fig. 7. Changes in the area proportion of trade-offs/synergies between pairs of ESs.

3.3. Identification of ESBs

Five types of ESBs were identified using the SOM technique (Fig. 8a), namely, CS regulating bundles (B1), CS-HQ-WY synergistic bundles (B2), WY provisioning bundles (B3), CS-HQ synergistic bundles (B4), and key synergistic bundles (B5). The area of interconversion between the five ESBs was quantified (Fig. 8b). While the areas of B2 and B4 shrank, those of B1, B3, and B5 expanded from 2000 to 2010. The change from B4 to B1 was most significant during this time. Although the rate of conversion between ESBs was high, the overall total area of ESBs did not change significantly. The ESBs shifted in the opposite direction from 2010 to 2020. The most significant shift during this period was the area of B1 that changed to no ESBs, which indicates that the CS regulation bundles are at risk of degradation. The total area of ESBs decreased by about 56,000 km^2 between 2010 and 2020.

Spatial analysis revealed significant spatial heterogeneity in ESBs (Fig. 9). CS regulating bundles were mainly distributed in oasis areas with a high level of anthropogenic disturbance at the edge of the Tarim Basin, where high vegetation cover increased the carbon sequestration capacity, while human activities increased the risk of degradation of CS bundles. The WY supply bundles were primarily distributed in the southern mountainous region, which is part of the Tibetan Plateau. Over the period studied, the area covered by WY supply bundles decreased significantly, mainly becoming an area in which no ESBs were located, which indicates that the WY supply bundles face the risk of degradation. The key synergistic bundles were primarily found in the northern part of the TRB in the Tianshan mountain and could provide multiple ESs simultaneously. The CS-HQ synergistic bundles were concentrated in the western and southern areas of the TRB, with a patchy distribution. The CS-HQ-WY synergistic bundles were distributed in small regions, primarily in the northern and southern mountainous areas. The regions without obvious ESBs mainly included the Gobi and desert areas. In summary, ESBs in the TRB exhibit obvious spatial heterogeneity, and the ES functions of each region are different. Therefore, when implementing ES management, it is necessary to implement effective management practices according to regional ES functions.

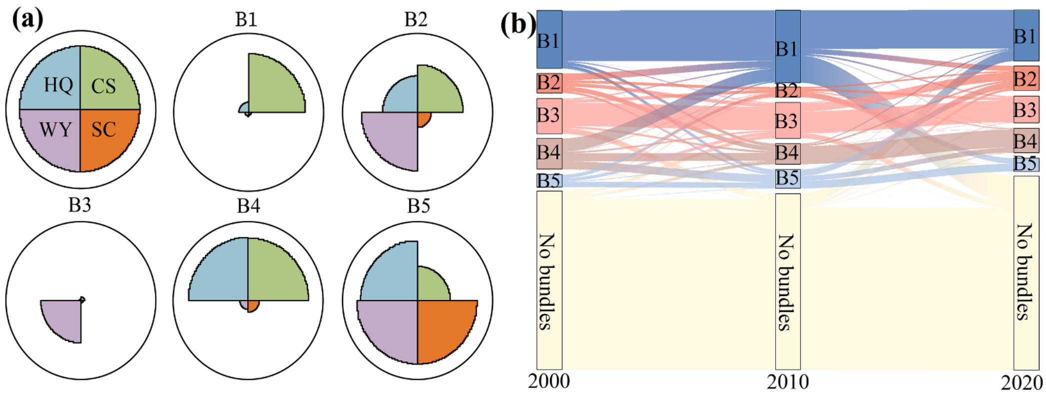

Fig. 8. ESBs from 2000 to 2020 in the Tarim River Basin. (a) Composition and proportion of each ES in the ESBs. (b) Transformation or degradation of each ESB from 2000 to 2010 and from 2010 to 2020.

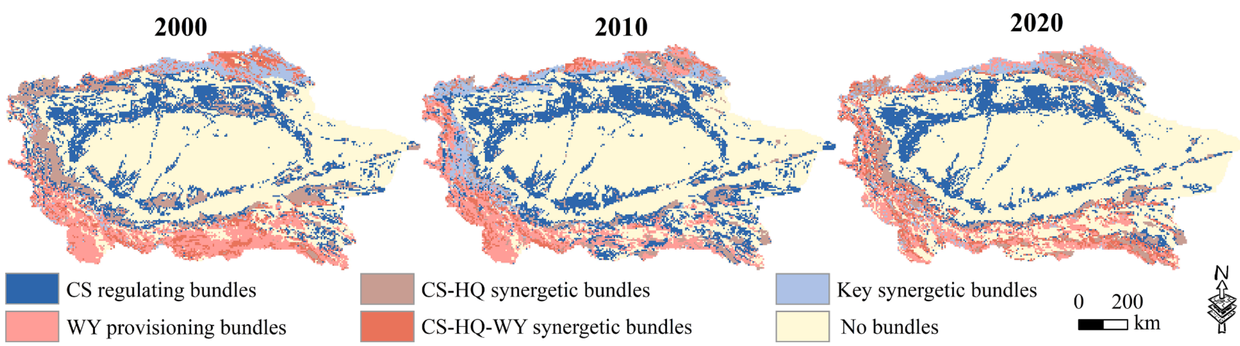

Fig. 9. Spatial distribution of ESBs.

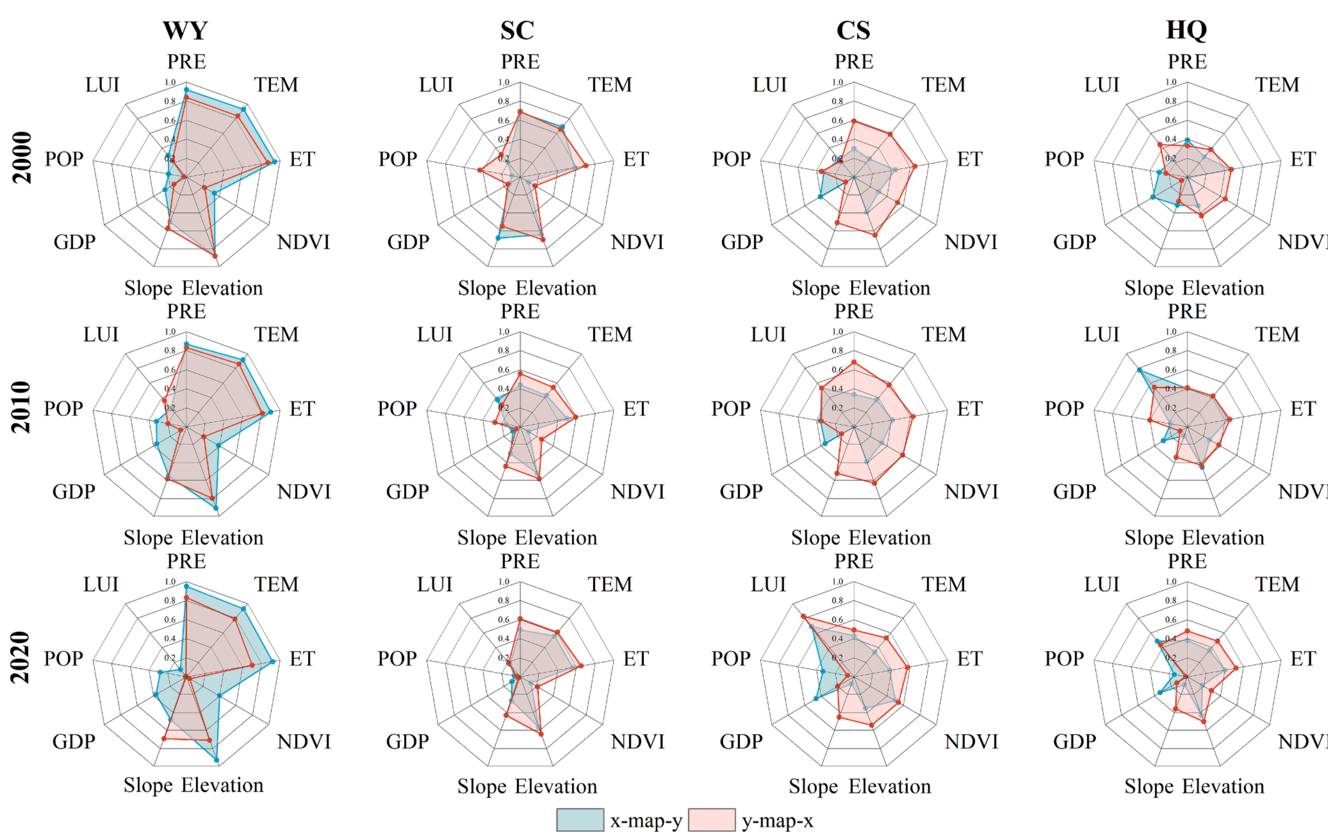

Fig. 10. Causal relationships between ESs and drivers. Note: y-map-x denotes the influence or reflection of x on y (x → y); x-map-y denotes the influence or reflection of y on x (y → x); x represents a driver or drivers, and y represents an ES.

3.4. Causality of ESs and drivers

The study utilized the GCCM approach to uncover the dynamic causality between ESs and drivers. The results of the study are as follows:

WY is an important supply service, with a predominant bidirectional asymmetric relationship with drivers, except for Slope, following the x-map-y (y → x) direction (Fig. 10, Table S7). In the TRB, natural factors are the primary drivers of WY (x-map-y, y → x), while anthropogenic factors have a lesser impact. Specifically, PRE, TEM, PET, and Elevation map WY is the dominant direction of the bidirectional asymmetric relationship with $\rho > 0.85$ ($p = 0.00$), and WY map PRE, TEM, PET, and Elevation with $\rho > 0.70$ ($p = 0.00$). WY can impact PRE, TEM, and PET through the hydrologic cycle and regional climate regulation, while these factors can also influence the WY, indicating a causal relationship. Elevation can influence the WY to a certain extent (causation), whereas the WY cannot directly alter the regional Elevation but may partially reflect it (reflection, non-causality). WY map Slope is the dominant direction of the bidirectional asymmetric relationship between WY and Slope with $\rho > 0.57$ ($p = 0.00$), and WY map Slope has a value of $\rho > 0.48$ ($p = 0.00$). Similarly, Slope can influence WY to some extent, while WY cannot directly change the regional Slope, it may partially reflect the Slope. NDVI, POP, GDP, and LUI map WY was the dominant direction of bidirectional asymmetric causality at $\rho > 0.1$ ($p < 0.05$), while WY map NDVI, POP, GDP, and LUI had smaller ρ values and did not pass the significance test of $p < 0.05$ in some years, which demonstrates that WY can influence regional vegetation conditions, human activities, and land use.

SC is an important regulating service. The overall bidirectional asymmetric relationship between SC and drivers was in the direction of y-map-x (x → y) (Fig. 10, Table S8). In the TRB, topographic and climatic factors are the primary influencers of SC, with vegetation and anthropogenic factors exerting less influence. Specifically, SC map PRE, TEM, ET, and Elevation is the dominant direction of the bi-directional asymmetric relationship, at $\rho > 0.54$ ($p = 0.00$), while PRE, TEM, PET, and Elevation map SC has a value of $\rho > 0.44$ ($p = 0.00$). PRE, TEM, and PET influence the regional SC, and vice versa, indicating a causal relationship. While Elevation can impact the regional SC, it is important to note that SC only partially reflects the Elevation. Except during the year 2000, the predominant direction of Slope and SC changed to SC map Slope, which exhibited a decreasing trend from $\rho = 0.55$ ($p = 0.00$) to $\rho = 0.43$ ($p = 0.00$). SC map NDVI exhibited the dominant direction of the bidirectional asymmetric relationship, showing a slightly increasing trend over the study period and rising from $\rho = 0.18$ ($p = 0.00$) to $\rho = 0.21$ ($p = 0.00$). Conversely, SC map LUI demonstrated the dominant direction of the bidirectional asymmetric relationship, with a decreasing trend from $\rho = 0.31$ ($p = 0.00$) to $\rho = 0.19$ ($p = 0.00$). The impacts of POP and GDP on SC showed a downward trend.

CS is an important regulating service, with a predominant bidirectional asymmetric relationship with drivers, except for GDP, following the y-map-x (x → y) direction. Natural factors are the major drivers for CS (Fig. 10, Table S9). However, the primary driver of CS in the study shifted from PET to LUI during the study period. This phenomenon was explained by the increasing alterations in LUCC caused by human activity, which resulted in higher LUI values. Consequently, LUI progressively emerged as the predominant factor influencing CS. GDP map CS is the dominant direction of the bidirectional asymmetric relationship, with ρ increasing from 0.41 ($p = 0.00$) to 0.46 ($p = 0.00$), suggesting that the influence of CS on the GDP is increasing. CS map POP decreased each year, while POP map CS became the dominant direction of the relationship at $\rho = 0.33$ ($p = 0.00$) by 2020. In general, land use and natural factors significantly influence CS, while human factors are influenced by CS.

HQ is an important supporting service, and x-map-y (y → x) is the dominant direction of the bidirectional asymmetric relationship between HQ and POP, GDP, and LUI. Conversely, the dominant direction with natural factors is y-map-x (x → y) (Fig. 10, Table S10). PRE, TEM, ET, Elevation, and Slope primarily impact the regional HQ in terms of climate and topography, with the strength of their influence growing over time. The HQ map NDVI showed a yearly decrease, from $\rho = 0.46$ ($p = 0.00$) to $\rho = 0.29$ ($p = 0.00$), suggesting a diminishing impact of the NDVI on the regional HQ. The bidirectional relationship between LUI and HQ changed from HQ map LUI to LUI map HQ over time. This shift is explained by the fact that regions with higher HQ tend to have better ecological conditions, leading to increased human interference in LUCC in those areas, thereby increasing the influence of LUI on HQ. The relationship between POP, GDP, and HQ is dominated by POP and GDP map HQ. Regions with higher HQ are more conducive to human activities, thus impacting the regional POP and GDP. Natural factors play a significant role in influencing HQ, while land use and human activities are influenced by HQ.

4. Discussion

4.1. Spatial heterogeneity of ESs and their trade-offs/synergies

The spatial patterns of ESs within the TRB varied (Fig. 3). The spatial patterns of SC and WY were similar, with gradual decreases from the mountainous areas to the central basin. CS mainly showed high values in mountainous areas and oasis zones, while high HQ values were found in patches in the mountainous areas. These findings are in concordant with previous research by Qian et al. (2024). The complexity and variability of regional climate, geomorphology, land use, and human activities can influence regional ESs, resulting in spatial heterogeneity in ESs within the TRB. PRE plays a significant role in WY (Yang et al., 2019). Accordingly, PRE and WY exhibited a strong spatial association. The spatial heterogeneity of WY was primarily determined by the distribution of PRE throughout space (Jia et al., 2023). In the TRB, mountainous areas receive more PRE compared to desert and oasis regions, resulting in the mountainous regions having higher WY values than the central and eastern regions. Fu et al. (2017) found similar trends in WY in the Altai region, where the mountainous areas receive higher PRE, leading to higher WY values compared to the desert and oasis regions. High SC values in the TRB were primarily located in the mountainous region, which is characterized by a stable land use structure with minimal human interference. These areas are predominantly covered by alpine meadows, which are essential to the preservation of local water and soil. SC is determined by both potential and actual soil erosion, which are influenced by several factors, including precipitation erosivity, soil erodibility, slope, slope length, and vegetation cover. In regions with poor vegetation cover, the potential for soil erosion is greater than the actual erosion, resulting in higher SC values. Therefore, higher vegetation cover does not necessarily indicate a greater capacity for soil and water conservation. CS in the TRB increased significantly over the study period. This increase is because of the successful realization of ecological water delivery projects beginning in 2000 and the efficient allocation of water resources since the implementation of these projects. These initiatives have met the ecological water demands of oases and agriculture, expanded agricultural production areas, promoted better crop growth, and increased the vegetation cover in oasis areas (Chen et al., 2021; Qian et al., 2024; Qiu et al., 2020). Lu et al. (2018) conducted a study on CS in six ecological restoration zones and determined that 56 % of carbon sequestration was primarily attributable to the implementation of ecological water delivery projects. In the present study, the areas with high vegetation coverage in the TRB exhibited higher HQ levels due to factors such as enhanced landscape connectivity, greater biodiversity, less construction land and cropland, and fewer ecosystem threats. Ecological water delivery projects have played a key role in the restoration of vegetation, thereby creating more habitats for a variety of organisms (Cai et al., 2021). In contrast, the desert area in the TRB lacked a suitable living environment for plants and animals, resulting in a lower HQ for the desert region.

This study examined the trade-offs and synergies among ESs by considering both the overall and spatial variations, aiming to enhance the understanding of their spatial heterogeneity. Although all the ESs in the TRB exhibited overall synergistic relationships with each other, spatial trade-offs and synergies also coexisted, showing notable spatial heterogeneity (Figs. 5 and 6). These results are similar to those of other regional studies (Li et al., 2022; Yuan et al., 2024). Synergistic effects between ESs are generally more beneficial for the sustainable development of ecosystems compared to trade-off effects (Liu et al., 2024). In this study, WY, SC, CS, and HQ exhibited strong synergistic relationships. The H-H synergies were concentrated in the Tian Shan and Kunlun Mountains, while the L-L synergies were prevalent in the central and eastern desert regions. The high levels of ESs in the mountainous areas of the TRB, in addition to favorable natural conditions and similar hydrological and ecological processes, contributed to consistent trends across ESs (Geng et al., 2022), leading to H-H synergistic relationships. Additionally, the mountainous regions of the TRB are abundant in glaciers and snow cover. As temperatures rise, increased snow and ice melt enhance hydrothermal conditions, promoting vegetation growth (Zhang et al., 2020). This improvement in environmental conditions has led to the expansion of H-H synergies in these areas. In contrast, the desert regions in the present study exhibited lower ESs and poorer natural conditions, leading to L-L synergies. Limited resources, the interdependence of ecological functions, and system complexity have resulted in distinct trade-offs between the oasis region and parts of the Kunlun Mountains. Ecological improvements in these mountainous areas have significantly reduced the area of trade-offs. Irrigated agriculture in the oasis region of the TRB supports carbon storage, but continuous tillage leads to higher water consumption, leading to the deterioration of the soil structure and stability, as well as declining HQ (Zubaida, 2024). This has intensified trade-offs, with an increasing trend over time. Because 98 % of the regional population resides in the oasis zone (Zhang et al., 2024), increased land use intensities have further exacerbated trade-offs in ESs (Felipe-Lucia et al., 2020).

4.2. Driving mechanisms of ESs

There is asymmetric causality between ESs and drivers. Each ES serves a unique function, resulting in varying causal relationships with drivers. ESs encompass provisioning, regulating, and supporting services, which are delineated by interactions between humans and ecosystems. ESs not only increase human well-being but also preserve the natural environment, which is necessary for human survival. ESs enhance ecosystem structure and climate regulation through offering a diverse array of functions. WY is essential for providing resources in ecosystems. In terms of the causal relationship between WY and drivers, the results of this study showed that the influence of WY on drivers was in the dominant direction, which was in line with the characteristics of the WY resource supply. SC, CS, and HQ are crucial in preventing soil erosion, enhancing carbon storage, and supporting biodiversity, respectively. Studies have shown that SC, CS, and HQ are influenced by natural factors, while LUI and anthropogenic factors are influenced by CS and HQ.

This study found that the climate significantly affected ESs in the TRB. ESs can also significantly affect the climate. According to the research of Zhang et al. (2022), rising climate extremes, droughts, and other natural disasters are causing ecosystems to become unsustainable. The TRB has experienced the depletion of water resources due to the extremely arid climate, resulting in reduced regional biodiversity (Yang et al., 2018). Climate change will exacerbate land degradation, water scarcity, and drought (Xue et al., 2017). Pan et al. (2013) discovered that precipitation is a key driver in regulating the overall quantity of ESs. Precipitation directly affects groundwater recharge and surface runoff (Bai et al., 2019), thereby affecting the stability of ecosystem structure and function. Temperature has an important effect on photosynthesis and organic matter synthesis in vegetation (Jia et al., 2023). Higher temperatures can enhance ESs, but these services may decrease or remain the same when temperatures surpass a specific threshold (Piao et al., 2014). This study revealed that elevation and slope had significant effects on the ESs in the TRB. The intricate topographic features of the TRB influence the spatial arrangement of vegetation, resulting in a distinct vertical zonation pattern. The vegetation in this region is highly responsive to climate fluctuations, which further explains the interaction among topography, climate, and vegetation. The NDVI is a crucial indicator of the health of regional vegetation. The growth of vegetation not only enhances the soil conservation capacity but also contributes to the improved quality of the environment. Vegetation contributes to carbon sequestration through photosynthesis (Fatichi et al., 2019), and releases water vapor via transpiration, thereby supporting biodiversity conservation. However, as vegetation continues to thrive, the increased water consumption may have implications for the regional WY. Given the limited scope and conditions for human activities within the TRB, the impact exerted by human activities on ESs is relatively minor compared to that exerted by natural factors. Humans benefit from ESs, but anthropogenic activities are restricted by regional natural resources, ecosystem quality, and climate. Moreover, human activities can greatly impact the spatiotemporal variability of ESs and exert pressure on ecosystems (Peng et al., 2017). ESs create a conducive environment for ecological processes and human endeavors, yet intense land use can lead to regional ecological degradation, ultimately impacting the functionality of ESs.

4.3. Suggestions for the spatial management of ESs

Uncovering the complex relationships between ESs is crucial for enhancing ES management (Raudsepp-Hearne et al., 2010). To prevent increased ES degradation in the TRB, some recommendations for the spatial management of ESs are proposed under the ecological protection measures that have been implemented and in conjunction with the results of this study. The synergistic areas of ESs in the TRB are primarily found in the oasis areas and southern mountainous regions, with localized distribution in the northern mountainous areas (Fig. 6). These areas are predominantly covered by grassland and farmland, with high vegetation cover. An increase in vegetation cover can enhance HQ and CS while improving soil erosion control. However, high vegetation cover may result in elevated ecological water consumption and reduced WY (Pei et al., 2022; Sun et al., 2006). The two most important determinants of ESs in the TRB are PRE and PET (Fig. 10). Vegetation growth and restoration in the TRB require large amounts of water, and the water supply cannot completely meet the water needs of the watershed. Considering that the TRB has low precipitation and high evapotranspiration, existing vegetation resources should be protected when implementing the policy of converting farmland into forest, and ecological restoration measures should emphasize planting vegetation with lower ecological water consumption. This strategic approach will enhance ES functions and help mitigate ecological water consumption.

Given the variations in ecosystem functions across different regions, it is crucial to implement differentiated management strategies for ESs. CS regulating bundles face the risk of degradation (Fig. 8b) and are mainly distributed in the oasis region (Fig. 9), which is dominated by cropland and grassland. Therefore, in the context of future development planning, it is recommended that low-carbon land use be regulated on a zonal basis, with the aim of land use optimization and the improvement of the level of regional carbon stocks; ecological restoration strategies should be implemented; excessive development should be limited in areas with high carbon stocks; and develop ecological agriculture to improve land quality. The WY supply bundle was concentrated around the southern mountains in the TRB (Fig. 9). The area was significantly reduced during the study period, indicating that the water source is at risk of degradation. Water source protection zones should be delineated in these areas to establish a comprehensive water source protection network, and measures to protect water source vegetation should be enhanced to enhance the overall water conservation capacity. The results showed that the CS-HQ synergistic bundles and CS-HQ-WY synergistic bundles were distributed in mountainous regions with patchy distribution. It is important to establish biodiversity protection networks, delineate ecological red lines, and minimize anthropogenic interference in these areas. The key synergistic bundles were primarily situated in the mountainous regions of the northern part of the basin, which serves as a crucial ecological barrier area. It is recommended to advance the establishment of ecological protection zones in this area; conserve alpine vegetation to enhance soil and water conservation capabilities; delineate ecological red lines, implement a stringent ecological compensation mechanism, and minimize human interference. Qian et al. (2024) discovered that the ESs of the TRB have been enhanced following the introduction of ecological water transfer measures The ecosystem has exhibited varying degrees of improvement as a result. Accordingly, further promoting the implementation of ecological water delivery projects on the TRB is necessary.

Although the impact of anthropogenic factors on ESs is much smaller than that of natural factors (Fig. 10), the influence of anthropogenic factors on ESs cannot be ignored. The WY, HQ, and CS are more susceptible to the effects of human activity on the TRB, with the LUI having the greatest impact on the HQ and CS. Li et al. (2018) identified grazing as a key factor in HQ degradation. To address this issue, it is recommended that the watersheds enhance policy implementation, such as adopting rotational grazing and converting pasture back to grassland, to integrate ecological conservation and restoration practices to facilitate the recovery of regional grassland ecosystems. Moreover, the construction of ecological projects and the growth of ecological industries should be promoted. It is imperative to establish a comprehensive biodiversity protection network in addition to ecological corridors. Scientific planning should be incorporated into the design of land use structures and the improvement of ecological land use connectivity. Natural factors have a strong influence on ESs, with climatic factors being the most important. There is a clear causal relationship between PRE, TEM, PET, and ESs. Therefore, ecological protection and restoration planning measures need to integrate the impacts of climate change on ESs.

4.4. Research limitations and prospects

This research provides a theoretical foundation and data support for the scientific management of ESs in the TRB while providing suggestions for the spatial management of regional ESs. However, this study has limitations and shortcomings. First, remote sensing data were employed to quantify ESs in this study. The quantified results were verified based on the Water Resources Bulletin and the results of previous studies, which showed a high degree of consistency. However, there may be inherent errors in the quantification of ESs due to limitations in the quality and resolution of remote sensing image data. Second, this research applied GCCM to examine the causality of ES and drivers, which provides a new perspective for studying ES drivers. While the findings demonstrated validity, the limitation of data accuracy may have introduced inaccuracies in calculating certain drivers. Finally, this research focused only on raster scale analysis and discussion, and the results may be biased if examined at different scales due to the scale effect. As a result, future research should consider conducting analysis and discussions of ESs at multiple scales to ensure the accurate implementation of spatial management strategies.

5. Conclusions

This study quantified four typical ESs in the TRB and analyzed the trade-offs/synergies and bundles between ESs. Based on the GCCM method, this work explored the causality of ESs and drivers and identified the key factors affecting ESs. The main conclusions are as follows:

(1) From 2000 to 2020, the WY and SC of the TRB showed a trend of increasing and then decreasing, with overall decreasing trends of 6.92 mm and 215.38 t/km^2, respectively; the CS increased significantly, with an overall increase of 60.20 t/km^2; and the HQ showed a decreasing and then an increasing trend, but with an overall insignificant change. Spatially, low values of the four ESs were concentrated in the central and eastern desert regions. High values of WY and SC were found in the mountainous areas with abundant precipitation, while CS and HQ peaked in both oasis and mountainous regions. The expansion of agricultural activities and the implementation of ecological water conveyance significantly boosted CS in the oasis areas, whereas intensified land use markedly reduced the HQ.

(2) The ESs in the basin showed significant synergistic relationships. Spatially, ESs exhibited both trade-offs and synergies. H-H synergies predominantly occurred in mountainous regions with extensive grass cover and favorable ecological conditions. Conversely, L-L synergies were mainly found in the central and eastern desert regions, which feature sparse vegetation and harsh natural conditions. The trade-off effect was primarily concentrated in the oasis areas and parts of the Kunlun Mountains. As the ecological conditions in the Kunlun Mountains improved over time, the area of trade-offs decreased. Conversely, increased agricultural activity and more intensive land use in the oasis expanded the trade-off area. The types of ESBs were transformed or degraded, with CS regulating bundles and WY supplying bundles at risk of degradation. This was largely due to extreme weather events caused by altered precipitation patterns under climate change, which adversely affected vegetation growth and the ecosystem's ability to sequester carbon.

(3) There were differences in the dominant direction of bidirectional asymmetric causality across ESs and drivers. The dominant direction of WY and its drivers was x-map-y (y → x), with WY as a supply service influencing or reflecting other factors, while SC exhibited the reverse relationship. The dominant direction of bidirectional asymmetric causality across CS and HQ with anthropogenic factors followed x-map-y (y → x). Conversely, the dominant direction of bidirectional asymmetric causality across natural factors followed y-map-x (x → y). The primary reason for this directional influence is that ESs contribute to human well-being, thus predominantly affecting human activities. The main drivers for WY and SC were found to be PET, PRE, TEM, and Elevation. The main drivers for CS and HQ were LUI, followed by PET, PRE, and TEM.

CRediT authorship contribution statement

Rongqin Yang: Writing – original draft, Visualization, Software, Methodology, Investigation, Funding acquisition, Conceptualization. **Zhenxia Mu:** Writing – review & editing, Supervision, Funding acquisition. **Rui Gao:** Writing – review & editing, Supervision, Conceptualization. **Mianting Huang:** Resources, Investigation, Formal analysis. **Shikang Zhao:** Resources, Methodology, Data curation.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2024.112810.

Data availability

Data will be made available on request.

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