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Spatio-Temporal Dynamics and Drivers of Ecosystem Service Bundles in the Altay Region: Implications for Sustainable Land Management

Suyan Yi ^{1,2} , Hongwei Wang ^{1,2,*} , Ling Xie ³, Can Wang ^{1,2} and Xin Huang ^{1,2}

¹ School of Geography and Remote Sensing Sciences, Xinjiang University, Urumqi 830017, China; yisuyan@stu.xju.edu.cn (S.Y.); wangcan_geo@stu.xju.edu.cn (C.W.); huangxin@stu.xju.edu.cn (X.H.)

² Xinjiang Key Laboratory of Oasis Ecology, Xinjiang University, Urumqi 830017, China

³ College of Environment and Resources, Guangxi Normal University, Guilin 541004, China; xl_geo@mailbox.gxnu.edu.cn

* Correspondence: wanghw_777@xju.edu.cn

Abstract: Understanding the dynamics of ecosystem services (ESs) in arid landscapes and socio-ecological systems is crucial for sustainable development and human well-being. This study uses the Invest model to quantify the spatio-temporal changes in four key ecosystems services in Altay from 1990 to 2020: water yield (water yield), carbon stock (carbon stock), soil retention (soil retention), and habitat quality (habitat quality). The trade-offs/synergies between different ESs were investigated via Spearman's correlation analysis. Ecosystem service bundles (ESBs) were mapped using self-organizing mapping (SOM), and the key drivers of ES relationships and the spatio-temporal dynamics of ESBs were revealed through redundancy analysis. The results showed that water yield increased by 33.7% and soil retention increased by 1.2%, while carbon stock and habitat quality decreased by 3.5% and 1.24%, respectively. The spatial distribution pattern had a clear zonal pattern, with the northern mountainous areas higher than the southern desert areas. The six pairs of ESs, in general, showed mainly low trade-off and high synergistic relationships, with trade-offs between water yield and carbon stock, soil retention and habitat quality, and a decreasing trend of trade-offs over time. Four types of ESBs were distinguished, and the compositional differences and spatial distribution within each ESB were determined by interactions between ESs and landscape types. There are complex non-linear relationships between the drivers and the four ESBs in different years. Before 2010, ecological factors were the key drivers influencing the spatio-temporal changes in ESBs, whereas social and environmental factors combined to drive changes in ESB allocations after 2010. Additionally, this study found that the implementation of conservation measures, such as reforestation and sustainable land management practices, positively influenced the provision of ecosystem services in the Altay region. These findings underscore the importance of integrating conservation efforts into land use planning and decision-making processes to ensure the sustainable delivery of ecosystem services in arid landscapes.

Keywords: ecosystem services; ecosystem services bundles; trade-offs; anthropogenic activities; spatial dynamics; Altay region



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1. Introduction

As global ecological and environmental issues become more prominent and sustainable development becomes more widely accepted, ecosystem services (ESs), as a theoretical and practical framework to solve human-land issues, play a vital role in advancing the agenda of social and environmental justice and achieving the sustainable development of socio-ecological systems [1–3]. ESs refer to various products and services that humans derive directly or indirectly from ecosystems, including provisioning, regulating, supporting, and cultural services [4]. The variety of ES types, the spatial heterogeneity of ES, and

human activities may generate complex interactions among ESs, which include trade-offs, synergies, and bundles [5]. In this context, exploring trade-offs/synergies in ecosystem services on the basis of long-term time series can help to prioritize conservation and restoration actions in areas where multiple services are under threat [6]. Remote sensing (RS) and geographic information system (GIS) technologies are becoming increasingly important in this field, not only to make up for the shortcomings of traditional monitoring data [7], but also to effectively track spatial and temporal trends in ecosystem services [8–10].

Ecosystem service bundles (ESBs), defined as spatially and temporally recurring collections of ESs [11], are an effective means of identifying patterns of multi-service aggregation in ecosystems [12,13]. ESBs are often quantified using cluster analysis [14,15], which captures the relationship of specific ESs to human-dominated land use and associated ESs [16]. In general, trade-offs and synergies between ESs are usually reflected in differences in the spatial distribution of ESBs and the intrinsic component of ESs. However, the direction and strength of these dyadic and synergistic ES relationships may be spatially heterogeneous and dependent on regional backgrounds [13]. ESBs provide a perspective for characterizing the complex interactions of multiple ESs and can be used to divide regions with homogeneous ES types and magnitudes. They also provide a solid foundation for effective spatial planning and decision-making to promote sustainable development and conservation efforts. Nonetheless, their composition, spatial distribution, and temporal dynamics are influenced by various drivers [17,18]. It has been reported that climate, vegetation, and human activities are important drivers of ESBs [19–21]. However, existing studies concentrated on regression analysis and scenario modeling to investigate the drivers of ESs, with some limitations. In regression analysis, the focus is often on linear relationships [22], yet this approach heavily is influenced by subjective human assumption [23]. Although interactions between drivers and spatial variations in driver effects have been considered in some studies [21], there is still a need to delve deeper into the spatio-temporal variability of ES clustering and its driving mechanisms. Understanding the driving mechanisms behind ESBs can provide valuable insights for enhancing ecosystem resilience and adapting to changing environmental conditions. Therefore, there is a critical need to refine our understanding of ESBs and the complex interactions of ESs within ecosystems.

The Altay region is a relatively abundant water area and a mountain grassland ecological function area in Xinjiang, which is composed of mountain–oasis–desert ecosystems by topography and climate. However, this region faces ecological challenges stemming from long-term mineral resource exploitation, grassland overgrazing, and oasis agriculture practices, compounded by anthropogenic and natural factors like climate change. These issues have resulted in the fragmentation of habitats and the degradation of forests, posing a threat to the sustainable social and economic development of the region [24]. Considering the rich ecological and functional complexity of this region, which is subjected to various external pressures, it is essential to conduct an in-depth investigation into the spatial and temporal evolution of ecosystem services in Altay, and the underlying driving forces, in order to discern the interconnections between diverse ecosystem services and the resulting socio-ecological impacts. This approach can facilitate a comprehensive understanding of the vulnerability of the regional ecosystems and their restoration potential, thereby providing a scientific foundation for the development of effective conservation and management measures.

2. Materials and Methods

2.1. Study Area

Altay region is situated in the northernmost part of the Xinjiang Uygur Autonomous Region, China. Its geographic coordinates are 85°31′–91°04′ E and 45°00′–49°10′ N (Figure 1). The Altay region has a natural geographic barrier in the north and an open terrain in the west, forming three major first-class geomorphological units: mountains, plains, and deserts. The mountain ranges vary in height from west to east, and the hilly plains gradually increase in elevation from east to west, presenting a more pronounced

stepped topography. Three main types of land use can be identified: forests, grasslands, and bare areas. To the south are vast deserts, while the northern mountains are rich in water resources and mixed tree–grass areas [24]. This region has a typical temperate continental climate, with average annual precipitation of 139.3–268.4 mm and average annual temperatures of 0.7–4.9 °C. Considerable inter-annual variability exists in runoff. In terms of spatial distribution, there are more water resources in the west and north than in the east and south [25]. The region has several nature reserves with many rare and endangered plants and animals, including the Castor fiber birulai, which is found only in the Ulungu River basin in northern Xinjiang, China [26]. The Altay Region consists of seven county-level administrative units. In 2020, the total population of the region was 668,600 people, and the gross domestic product (GDP) reached CNY 33.632 billion. The expansion of human activities, such as tourism development and agricultural production, has resulted in the degradation of biological habitats to some extent.

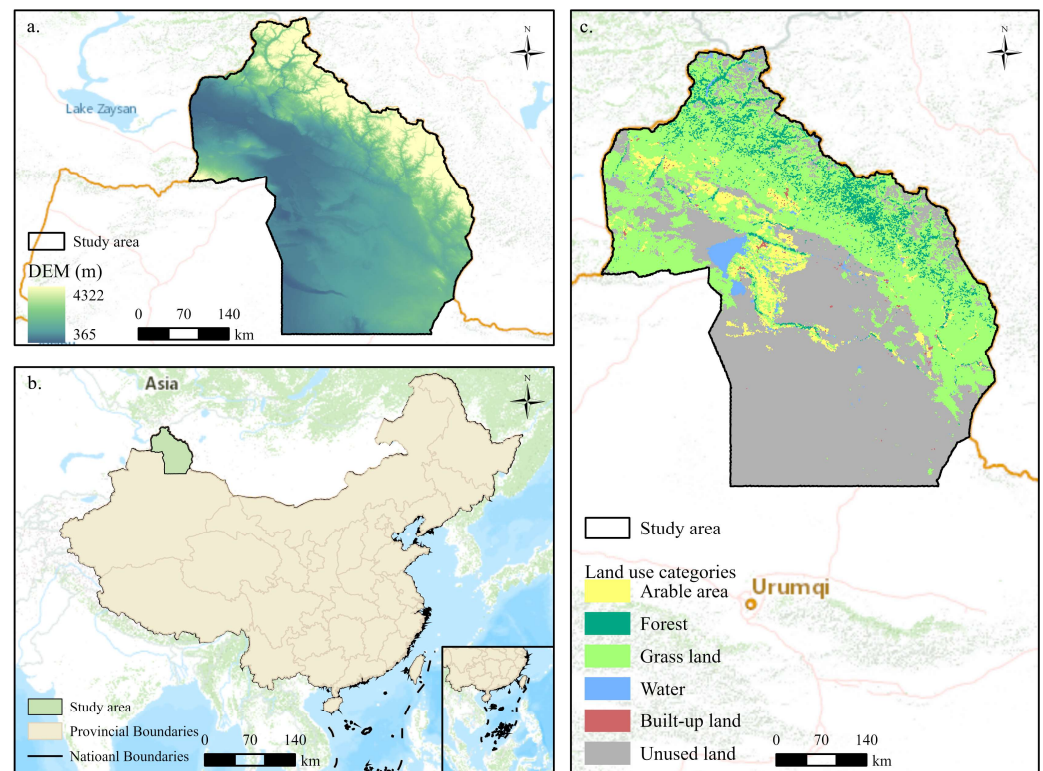


Figure 1. Location of the Altay region in China. (a) Elevation distribution; (b) map inspection number GS (2019) 1822; (c) land-use categories of Altay in 2020.

2.2. Data Sources

In this study, ESs and socio-ecological drivers were quantified using multi-source data on land use/land cover, climate, vegetation, and socio-economics from 1990 to 2020 (Table 1). The land use/land cover data represent 25 thematic categories. All the raster data with different spatial resolutions in Table 1 were resampled to have a standard spatial resolution of 1 km × 1 km for quantifying ESs and the spatio-temporal socio-ecological drivers.

Table 1. Data sources for this study.

Data Type	Application	Data Format	Data Source/Processing	Spatial-Resolution
Land use/land cover	water yield, carbon stock, soil retention, habitat quality, social–ecological drivers	Raster	Resource and Environment Science and Data Center (http://www.resdc.cn (accessed on 3 June 2024))	30 m
Precipitation	water yield, social–ecological drivers	Raster	National Earth System Science Data Center, National Science & Technology Infrastructure of China (http://www.geodata.cn (accessed on 3 June 2024))	1 km
Temperature	social–ecological drivers	Raster	National Earth System Science Data Center, National Science & Technology Infrastructure of China (http://www.geodata.cn (accessed on 3 June 2024))	1 km
Evapotranspiration	water yield, social–ecological drivers	Raster	National Earth System Science Data Center, National Science & Technology Infrastructure of China (http://www.geodata.cn (accessed on 3 June 2024))	1 km
Root depth, soil texture, and organic carbon content	water yield	Raster	China soil map based harmonized world soil database (HWSD) (v1.1)	30 arc-second
Carbon density	carbon stock	Spreadsheet	A dataset of carbon density in Chinese terrestrial ecosystems (2010s) (http://www.doi.org/10.11922/sciencedb.603 (accessed on 3 June 2024))	/
Digital elevation model (DEM)	soil retention, social–ecological drivers	Raster	Resource and Environment Science and Data Center (http://www.resdc.cn/ (accessed on 3 June 2024))	90 m
Normalized difference vegetation index (NDVI)	social–ecological drivers	Raster	Resource and Environment Science and Data Center (http://www.resdc.cn/ (accessed on 3 June 2024))	1 km
Gross domestic product (GDP)	social–ecological drivers	Raster	Resource and Environment Science and Data Center (http://www.resdc.cn/ (accessed on 3 June 2024))	1 km
Population density	social–ecological drivers	Raster	Resource and Environment Science and Data Center (http://www.resdc.cn/ (accessed on 3 June 2024))	1 km

2.3. ES Quantification

In this study, four ES categories of the region were finalized based on the variability of geomorphology, climate, vegetation, water system, and intensity of anthropogenic disturbances, i.e., water yield, soil retention, carbon Stock, and habitat quality (Table 2). With the help of the InVEST software (3.7.0), the ESs in 1990, 2000, 2010, and 2020 were quantified, and the spatial distribution pattern of ES, interaction characteristics, and major ecological threats were then analyzed.

Table 2. Overview of ecosystem services.

Ecosystem Service	Description
Water yield	The yield of annual water
Habitat quality	The ability of ecosystems to provide conditions suitable for the persistence of individuals and populations.
Carbon storage	The amount of carbon stored by terrestrial ecosystems
Soil retention	Sediment delivery ratio

2.3.1. Water Yield (WY)

Using the water balance method, the annual water production of the Altay region was estimated based on the “water harvesting” module of the InVEST model, and the water conservation capacity of the Altay region considering the streamflow, soil permeability, and other factors (Equations (1)–(2)) [27]:

$$WY = \min(1, 249/\text{Velocity}) \times \min(1, 0.3\text{TI}) \times \min(1, K_{\text{sat}}/300) \times Y_x \quad (1)$$

$$Y_x = (1 - \text{AET}_x / P_x) \quad (2)$$

where WY is water yield (mm), Velocity represents flowing rate, TI is topography index, K_{sat} is saturated hydraulic conductivity of soil (mm/d), Y_x denotes annual water yield (mm), AET_x is average annual actual evapotranspiration of grid cell x (mm), and P_x indicates average annual precipitation of grid cell x (mm).

2.3.2. Soil Retention (SR)

In the current work, the soil conservation module of the InVEST model was employed to calculate the average annual soil loss and soil conservation for each land-class grid using geomorphic, climatic, vegetative, and management capacity data, primarily based on the Universal Soil Loss Equation (USLE) (Equation (3)) [28]:

$$SR = R \times K \times LS \times C \times P \quad (3)$$

where SR is the soil erosion volume; R is the rainfall erosive force; K is the soil erodibility factor; LS is the sloping length factor; C is the vegetation cover factor and management factor; and P is the soil and water conservation measures factor.

2.3.3. Carbon Stock

Carbon sequestration model in InVEST was adopted for assessment. This model was constructed based on the main principle of accumulation of carbon densities, including surface carbon density, soil carbon density, subsurface carbon density, and dead carbon density.

2.3.4. Habitat Quality

The habitat quality module of the InVEST model was used to assess habitat quality in the Altay region. This model links habitat distance and threat sources to compute habitat quality (Equation (4)) [29]:

$$Q_j = H_j \left(1 - \frac{D_j^2}{D_j^2 + k^2} \right) \quad (4)$$

where Q_j is the habitat quality of land use type j; H_j is the habitat suitability of land use type j; D_j represents the level of stress to which land use type j is subjected; and k is the half-saturation constant.

2.4. Quantification of Relationships between ESs

The interactions among the four ESs are subject to uncertainty and thus require a dynamic understanding of their relationships. Spearman correlation analysis was employed to assess the correlations between the four ESs [14,18]. The “Corrplot” package in R software (4.3.3) was used to calculate the Spearman correlation coefficient.

2.5. Identification of ESBs

To facilitate comparison between different years, ESs were normalized from 0 to 1 (low to high); a total of 4898 ecological grid units of 5 km × 5 km each were partitioned within the study area by using the grid method. We conducted self-organizing mapping analysis using the “kohonen” package from software R (4.3.3).

2.6. Identification and Analysis of Socio-Ecological Drivers of ESBs

Potential socio-ecological drivers affecting ESB formation were categorized into three groups, i.e., landscape configuration, natural ecology, and human activity indicator. To reduce the redundancies among the indicators and to identify the main drivers, SPSS (26.0 software) was used to diagnose multiple covariances, eliminating indicators that had a VIF of >10 [30], leaving twelve possible social–ecological drivers for further analysis (Table 3).

Table 3. Social–ecological drivers.

Category	Indicator	Abbreviation
Biophysical indicators	Topographic position index	TPI
	Normalized difference vegetation index	NDVI
	Drought index	K
	Temperature	TEM
Anthropogenic indicators	Land-use development intensity	LDI
	Population density	POP
	Gross domestic product	GDP
	Human activity intensity	HAI
Landscape configuration	Aggregation index	AI
	Contagion index	CONTAG
	Patch density	PD
	Number of patches	NP

To facilitate comparisons between years, potential drivers were standardized [14,31] and then used to perform redundancy analyses (RDAs) to select different combinations of key social-ecological drivers that significantly affect ESs in different ESB types. For each ESB, socio-environmental drivers were identified and tested for significance (999 permutations). The results were used to check the statistical significance of these factors. In addition, hierarchical partitioning analyses were conducted to obtain independent explanations for each socio-ecological driver of multiple ESs in each ESB.

3. Results

3.1. Spatial–Temporal Variations in ESs

In this study, four ES categories (including water yield, soil retention, carbon stock, and habitat quality) were quantitatively analyzed. The results showed that the spatio-temporal patterns of ESs were heterogeneous. Over the past 30 years, water yield and soil retention in the Altay region showed an inverted U-shaped trend (Figure 2a,b). From 1990 to 2000, there was a significant increase in both soil retention and water yield values. Water yield increased by 29.27% and soil retention by 32.44%. However, from 2010 to 2020, the soil retention value showed a decreasing trend, decreasing by 2.27%, while the water yield value decreased by 29.12%. Compared to 1990, the total soil retention and water yield in the region increased by 33.7% and 1.2%, respectively, in 2020. Changes in carbon stock and habitat quality showed consistency across years (Figure 2c,d). The peak year was 1990, showing the lowest value by 2020. Carbon stock and habitat quality showed similar rates of decline, with decreases of 3.5% and 1.24%.

According to the spatial distribution map, water yield and soil retention show similarities, with high values in the north hilly regions and northwestern mountainous regions, while low value regions are clustered in the plains and desert of the south and center (Figure 2a,b). It was evident that the water yield amount in the northwestern region was significantly more increased in 2010 than in the other years (Figure 2a). The overall distribution pattern of carbon stock in Altay showed a gradual decline from north to south (Figure 2c). Areas with high carbon stock values are distributed in the northeast, with water systems in the west belonging to the mountainous forested areas with high vegetation cover and a more complete landscape. The main distribution area of desert is located in the south, which is also the distribution area with low carbon stock and habitat quality

values. In contrast, the central region exhibits more apparent fluctuations in carbon stock and habitat quality.

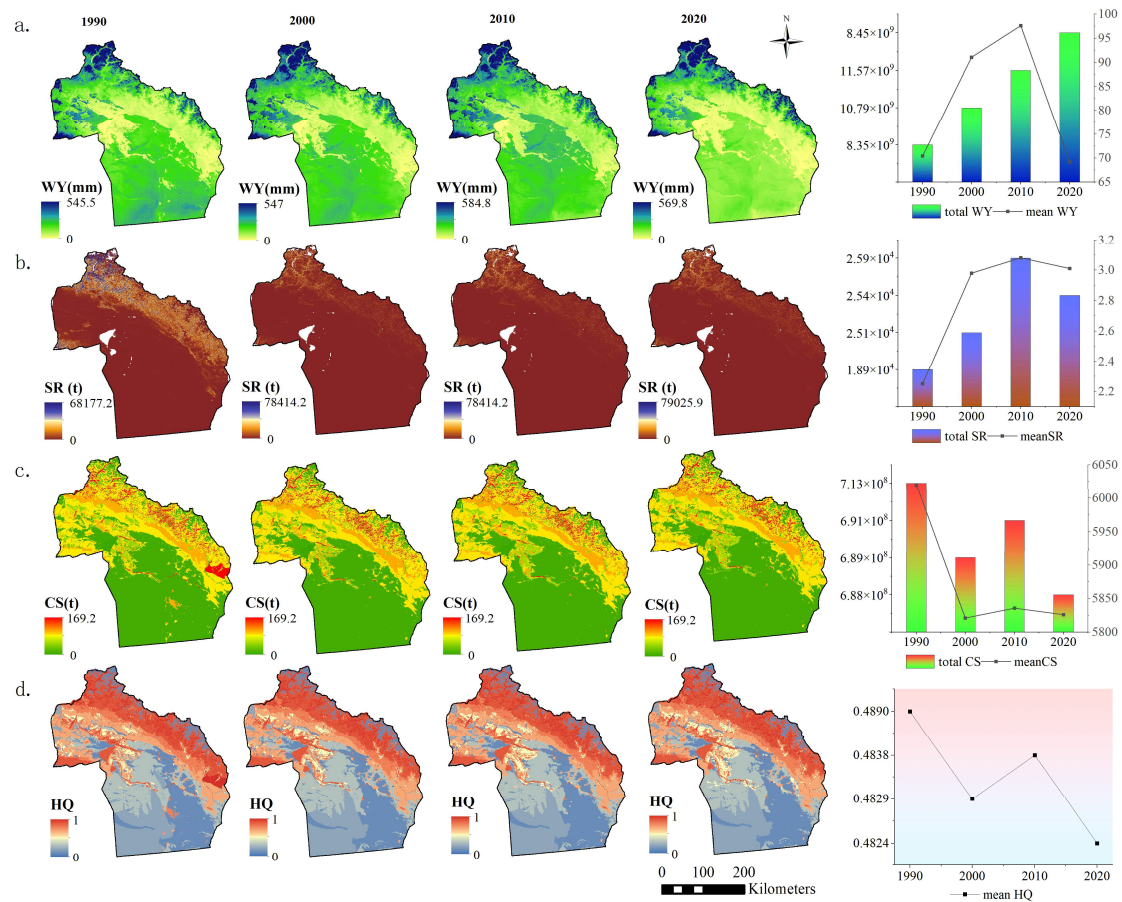


Figure 2. Spatial-temporal patterns and variability in ecosystem services. (a) WY: water yield; (b) SR: soil retention; (c) CS: carbon stock; (d) HQ: habitat quality.

3.2. Trade-Offs and Synergies between ES Pairs

By quantifying the correlations between the five categories of ESs in different historical periods, we found statistically significant ($p < 0.001$) correlations between six ES pairs (Figure 3). Carbon stock, habitat quality, and soil retention all exhibited synergies with each other, while water yield showed a trade-off with these three ES categories, with the highest trade-offs between water yield and carbon stock, and the lowest between water yield and soil retention. During 1990–2020, the trade-offs between water yield and carbon stock, habitat quality, and soil retention weakened. Notably, the highly significant negative correlation between water yield and carbon stock shifted to a highly significant positive correlation. The synergy between soil retention, carbon stock, and habitat quality has shown a stable trend. Overall, the relationship between these four ESs in the Altay region is characterized by low trade-offs and high synergies. There is a clear conflict between water yield on one side and carbon stock, soil retention, and habitat quality on the other side, leading to a gradual weakening of the trade-offs over time.

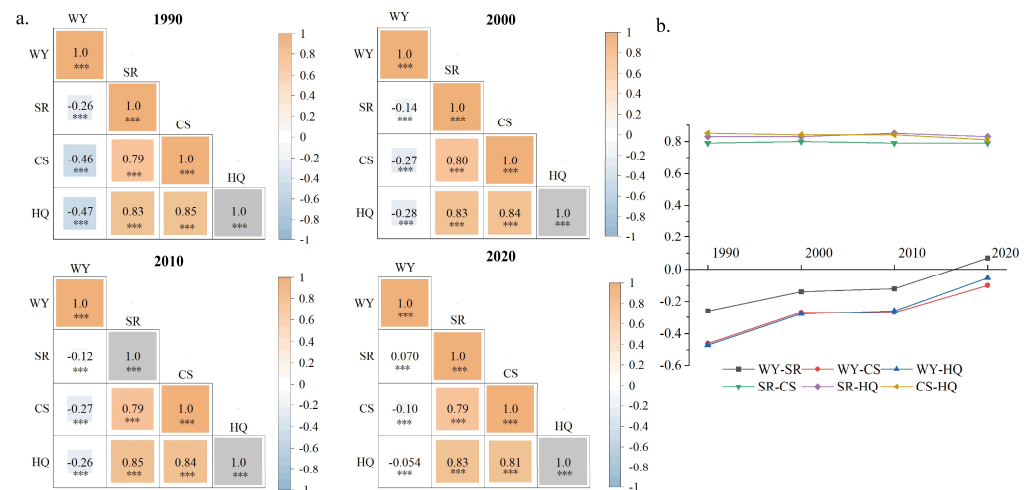


Figure 3. (a) Trade-offs and synergies among the relationships of ecosystem services in the Altay region from 1900 to 2020; (b) Correlation changes in 1990 to 2020. *** $p < 0.001$.

3.3. Spatial–Temporal Distributions of ESB

The self-organizing mapping identified four ESB bundles at the grid scale, and the trajectory change in ESBs from 1990 to 2020 was further explored based on the classification result (Figure 4a). According to the ESB composition (Figure 4b), bundle 1 includes three types of ESs, including soil retention, carbon stock, and habitat quality; this bundle demonstrated the spatial synergy of high soil retention, carbon stock, and habitat quality. The distribution of bundle 1 was mainly concentrated in the gentle mountainous regions and low hills. Bundle 2 is widely distributed in the south-central region and displayed a distinct vertical pattern. It was characterized by a sizable supply of water yield and habitat quality, with carbon stock being less prominent. Bundle 3 has a more limited function type, consisting only of soil retention and water yield, with soil retention's proportion being much higher than that of water yield. This bundle has the smallest area and highly concentrated spatial distribution. Bundle 4 was primarily spread across the mountainous regions with high elevation in the northwest and has the most balanced distribution of proportions of each type of ES, demonstrating its ability to provide an integrated ES advantage. The spatial variation in the four ESBs is mainly concentrated in the gently sloping mountain and oasis regions.

Figure 5 reflects the shift in area of different ESBs at the grid scale and the proportion of landscape types from 1990 to 2020. Over the past 30 years, the change in the area covered by Bundle 1 has exhibited a consistent pattern with the change in the area of forests within its corresponding landscape type. Bundle 2 exhibits the highest proportion of unused land in the regional landscape type, which is primarily composed of bare rock and sandy soil. The Gobi encompasses a considerable area of undeveloped wasteland, resulting in a lower proportion of soil retention in this bundle. The landscape composition of bundle 3 is dominated by river, which accounts for more than 50% of the area. Bundle 4 exhibits the greatest proportion of forested grassland in comparison with the other three ESB landscape types, displaying an upward and subsequent downward trend in the change in its area.

From 1990 to 2000, the land use type of the region where bundle 1 is located exhibited a higher proportion of forests and grasslands. Concurrently, the area occupied by bundle 1 decreased by 11.6% due to an increase in the proportion of unused land. In contrast, the area of bundle 4 exhibited an increasing trend, accompanied by an increase in the proportion of forests in the landscape type and a concomitant decrease in the proportion of unused land. The reduction in bundle 1 was accompanied by an increase in the areas of bundle 2 and bundle 4 (Figure 5e). The area covered by bundle 1 showed an increasing trend from 2010 to 2020, which was reflected in a decrease in the share of cropland and an increase in the share of forests in its land use type. The area covered by bundle 4 was

the highest in 2010, with an area share of 9.7%. This was mainly due to an increase in the proportion of grassland, a continuous decrease in the proportion of unused land, and an increase in vegetation cover. The proportion of area covered by bundle 2 was 51.1% in 2020, with the proportion of arable land showing an increasing trend and the proportion of unused land showing a decreasing trend.

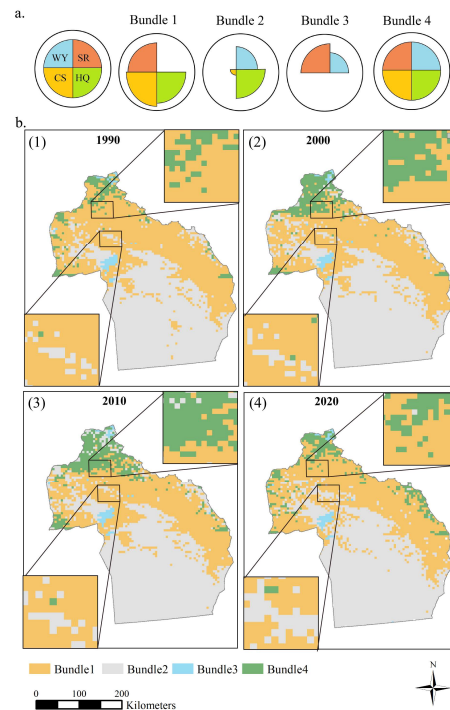


Figure 4. (a) Composition and relative magnitude of ESs in ES bundles at the grid scale; (b) the area of inter-conversion among different ES bundles in 1990–2020 at the grid scale.

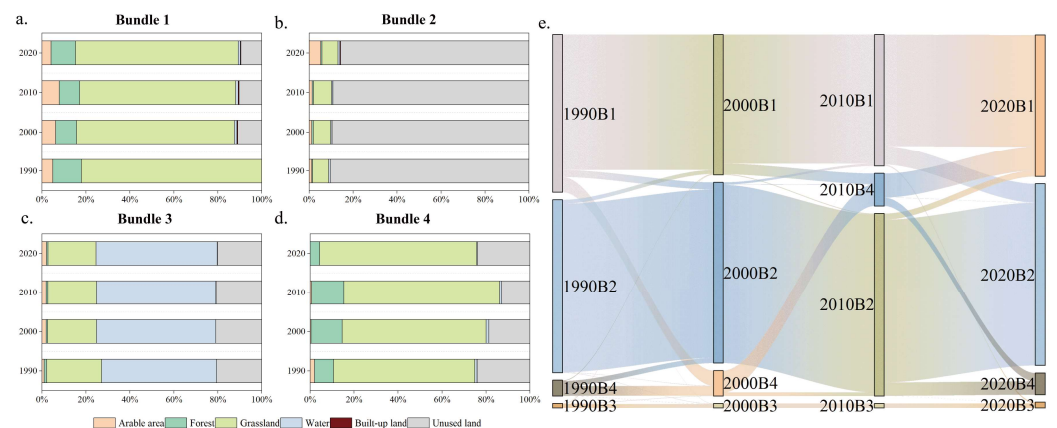


Figure 5. (a–d) Spatial-temporal patterns of ES bundles at the grid scale; (e) land-use structures of the landscapes with different bundles of ecosystem services in 1990–2020.

3.4. Drivers of the Spatio-Temporal Heterogeneity of ESBs

The proportion of socio-ecological factor composition was found to significantly affect the distribution of ESBs (p -value < 0.05). Moreover, the explanatory power of different socio-ecological drivers in ESBs similarly varied (Figure 6). This suggests that the same drivers may show consistent effects on some ESs across the four ESBs over time, or they may have opposite effects on the same function across ESBs. The RDA demonstrated inter-annual fluctuations in the explanatory potential of the 12 socio-ecological factors for different ESBs and the four types of ES. The initial two principal components (RDA1 and

RDA2) accounted for a substantial proportion of the data variability observed in the distinct ESBs (Figure 7).

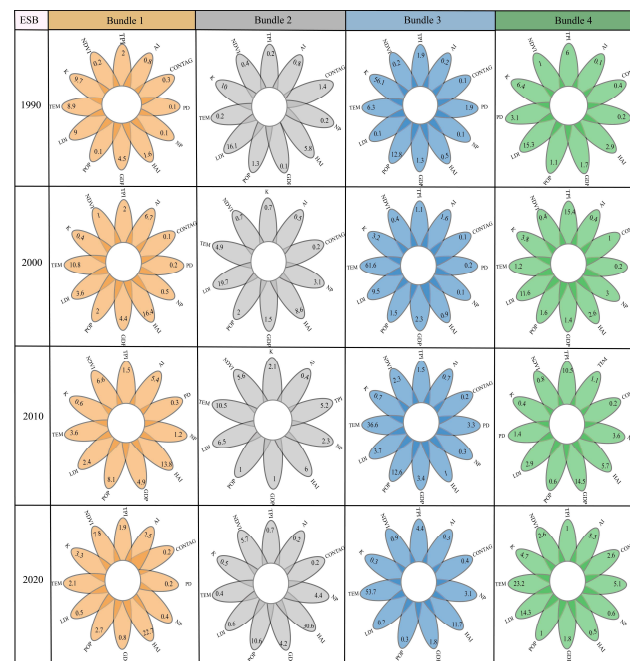


Figure 6. The explanatory ability of socio-ecological drivers for ESBs in Altay (1990–2020).

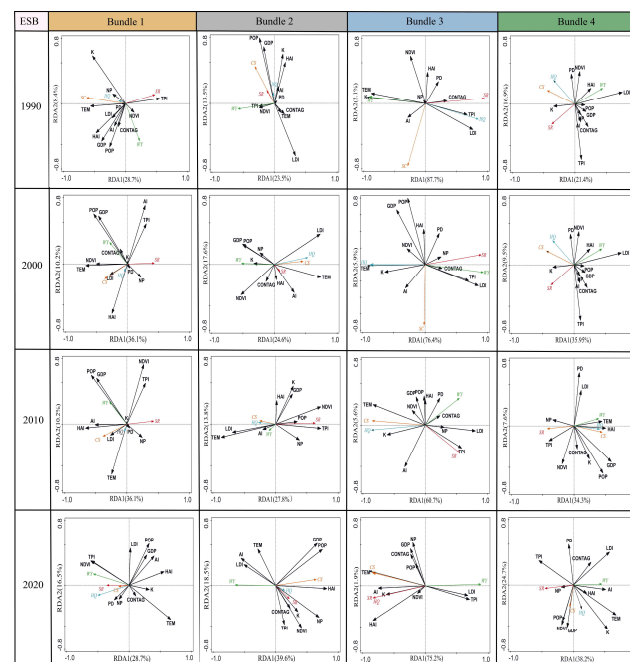


Figure 7. Impact of socio-ecological drivers on ESBs in Altay (1990–2020).

During 1990–2000, the main drivers affecting the changes in bundle 1 and bundle 3 were K and TEM, respectively. The contribution of K demonstrated an upward trajectory, while the explanatory potential of NP and PD was less than 2%. The spatio-temporal drivers of bundle 2 were mainly K and LDI. In this case, the influence of K exhibited a decreasing trend, while the influence of LDI gradually increased. The key drivers affecting changes in bundle 4 were TPI and LDI, with the influence of TPI increasing significantly and a contribution rate of 15.4% in 2000. From 2010 to 2020, the main drivers affecting

bundle 1 were HAI and NDVI. The effect of these drivers gradually increased. For bundle 2, in addition to LDI, the HAI driver has become one of the key drivers. For bundle 3, the social driver POP became a key driver in 2010, along with the impact of the ecological driver. However, the social driver of this cluster changed from population density to HAI in 2020. For bundle 4, the social driver was replaced by GDP from the previous LDI, and the impact of the social driver exceeded the impact of the ecological driver, contributing 23.2% in 2020.

The positive and negative effects of different driving factors on the improvement in ESs in different ESBs fluctuate or have phased effects, eventually leading to the spatio-temporal differentiation of ESBs. For some ESBs, the driving factors will change over time, and even the driving mechanism of the same factor will evolve. This shows that the driving factors have different nonlinear effects on ESs in different years.

For ESs comprising internal ESBs (Figure 7), K and TEM are the primary negative drivers influencing the quantity of water yield, namely the greater water yield in low-temperature, low-dryness regions. NDVI was positively correlated with water yield, carbon stock, and habitat quality, suggesting that the greater the vegetation cover in the region, the higher the corresponding ES function. In 2010 and 2020, the status of LDI reversed from a positive indicator to a key negative indicator, with the exception of TEM, in regulating soil retention. On the other hand, TPI emerged as the primary positive indicator influencing soil retention, showing a negative impact on water yield, carbon stock, and habitat quality. The contribution of HAI to each ES is uncertain. In 2010, POP became the main determinant of the number of water yield reverse drivers, while GDP was positively correlated with water yield and habitat quality in 2020.

In summary, the driving factors of bundles 1, 2, and 4 have shifted from being primarily ecological factors to being jointly driven by social and ecological factors. On the contrary, the driving factors of bundle 3 remain relatively stable. Among the ecological factors, K, TEM, NDVI, and TPI are the main driving factors of ESBs and ESs. In contrast, the social factors of LDI, HAI, GDP, and POP have more significant driving effects.

4. Discussion

4.1. Spatio-Temporal Changes in ESs and Interaction Characteristics

The water yield, soil retention, carbon stock, and habitat quality exhibit distinct spatial heterogeneity characteristics due to the geographical differentiation of the natural environment. This has led to the development of a unique arid “mountain–oasis–desert” system in the Altay region [24]. The northeastern mountainous areas are characterized by high ES values and high forest coverage rates. Despite strong rainfall erosion, lower evapotranspiration contributes to soil conservation, resulting in higher water yield and soil retention values [31]. In addition, high soil retention areas were significant in the northern region and closely associated with areas of steep slope, suggesting a correlation between soil retention and topography. Conversely, land degradation affected the southern region, resulting in low vegetation cover, mainly unused land, leading to high ecological degradation and low carbon stock and habitat quality values. Changes in land cover types significantly affected the capacity of carbon stock services in different areas. Where forests and grasslands are found in the north and south of carbon stock, there is more variety in the value distribution than elsewhere. This study also reveals that ES variations are primarily concentrated within high-value ES zones, followed by central oasis areas. This phenomenon suggests a heightened sensitivity towards disturbances within these locations due to the impact of significant human activity, as previously indicated [32]. The traditional seasonal grazing practices of Altay herders, particularly during the spring and summer months, have led to significant damage to the high-elevation grasslands and alpine meadows [33]. And the expansion of agricultural land, urbanization, livestock grazing, and other factors has resulted in a reduction in carbon stock, water yield, and habitat quality, ultimately leading to a decline in ESs [34].

This study also reveals the interactive relationships between ESs in the Altay region from 1990 to 2020. There is a trade-off between water yield and soil retention, carbon stock, and habitat quality, which is mainly influenced by precipitation and land cover [35]. Changes in climate and land use conversion impact regional vegetation coverage, leading to significant splash erosion and scouring from excessive precipitation that can result in a decrease in soil retention [36]. Meanwhile, population growth and economic demands have led to an increase in the intensity of human activities, the destruction of vegetation growth conditions, and increased soil erosion, while retention has gradually declined. Studies in arid inland river basins have reported similar findings [37]. Soil erosion is also a major problem faced by the ecology of the region today [38–40]. It is noteworthy that the high trade-off relationship between the two types gradually converged to a low synergistic relationship between 1990 and 2020, suggesting some potential for ecological optimization in the region. Jia et al. showed that constructing ecological restoration projects, such as the Grain for Green Project in China, has the potential to alleviate the trade-off between water yield and soil retention [41]. Additionally, the initiation of these projects in 2000 coincided with the observed trend of changes in the relationship strength of trade-offs between ESs in the study region [42]. The synergistic relationships in the Altay region are reflected in the relationships between soil retention, carbon stock, and habitat quality. The synergistic relationship between carbon stock and soil retention in the Altay region is due to the increase in vegetation cover, which enhances carbon stock and reduces rainfall-induced soil erosion, thus enhancing soil retention [43]. Soil retention maintains a stable level of species diversity and improves the development of habitat quality [44].

4.2. ESBs and Dynamic Drivers in Land Management

This study found significant variations in the types and proportions of ESs provided by different ESBs. Furthermore, ESBs exhibited multi-dimensional and multi-temporal correlations [45]. The dynamic changes observed can reflect the potential causes of ES changes and the speed of change. Identifying the social drivers of ESBs is favorable for formulating spatial management and planning strategies that promote the multifunctionality of the research area and enable the sustainable development of the region [46,47].

It was shown that water yield exhibited a trade-off relationship with soil retention, carbon stock, and habitat quality, in accordance with the internal ES composition of bundle 1. K and TEM exhibited a more pronounced driving effect on bundle 1. The warming and drying climate conditions led to a decline in ESs, and drought exacerbated the risk of desertification, posing a greater threat to the ecological security of oasis regions [25]. Since 2010, NDVI has become the main positive driving factor for bundle 1; ecological protection projects (e.g., the “Grain for Green” project) have expanded the area covered by vegetation and vegetation restoration enhances the synergistic benefits between carbon stock and water yield in the arid northern region [48], enhancing the ESs of the region and facilitating the transition from bundle 1 to bundle 4. According to ESB classification, bundle 1 is spanning the mountain oasis ecological zone and river buffer zone. Under the impact of climate change and water resource inequality, the ecological functions of the region are severely limited. The rapid expansion of urban construction areas due to intensified human activities has significantly altered the spatial pattern of ESBs in the region. For bundle 1, future management should prioritize soil conservation, restrict grazing activities [49], and make efforts to restore vegetation in areas of severe land fragmentation. Furthermore, it may also be beneficial to consider expanding the Altay Nature Reserve to limit human activities and increase the stability of vegetation in order to mitigate the impact of climate change [50].

The internal composition of bundle 2 includes water yield, habitat quality, and carbon stock, whose distribution area is subject to a combination of environmental constraints and anthropogenic interventions. LDIs and HAIs are key socioeconomic factors influencing the spatial differentiation of bundle 2, highlighting the significant impact of complex human activities on ecological disturbance [51]. The expansion of the build-up area has caused

a reduction in carbon stock, leading to a decrease in regulatory services [52]. Meanwhile, the increase in surface hardening has contributed to an upward trend in water yield [53]. This suggests that the advancement of regional economic development has contributed to the implementation of ecological conservation policies, thereby facilitating ecosystem restoration and reconstruction. The land-use structure should be adjusted based on ecological suitability and environmental carrying capacity in order to alleviate the ecological stress caused by construction expansion.

As a crucial source of water supply, bundle 3 is primarily driven by K and TEM. Despite increased rainfall amounts across much of the Altay region experiencing arid climates with evaporative rates often surpassing actual rainfall totals, drought-induced water scarcity hampers vegetation growth, while adverse ecological impacts due to climate warming are emerging [54]. As the distribution of ESBa is concentrated in riverine landscapes comprising watersheds and other land use types, the limited interception of runoff facilitates water storage due to low-to-moderate grass cover. Management objectives should adhere to the principle of ecological prioritization, focusing on water retention and storage.

Bundle 4 is predominantly distributed in high-altitude mountainous areas, which serve as primary sources of ecosystem services, with the high-altitude northern glaciers providing abundant water and thermal resources [33]. TPI exerts a positive driving force in the formation of bundle 4, topographically redistributes water and thermal conditions, influences soil properties, and leads to interannual variations in soil retention, thus playing a crucial role in the spatio-temporal patterns of bundle 4. Bundle 4 is also in an area with excellent natural conditions, where human interventions have led to changes in land cover, consisting mainly of forests and grasslands. In 2000, China began to implement the “Grain for Green” project, and the supply and regulation services in the Altay region were improved [17]. Future management objectives should take into account the establishment of an ecological red line, the active protection of the pristine ecological environment, and the restriction of the artificial and unreasonable expansion of the northwestern mountainous areas. These actions are necessary to promote environmental protection and sustainable development. Additionally, in order to safeguard or enhance the carbon sequestration surplus in densely vegetated areas, it may be beneficial to consider utilizing carbon trading platforms and fiscal transfer payments as a means of providing or enhancing ecological compensation for establishing ecological redlines [55,56].

5. Conclusions

In the current study, we analyzed the spatio-temporal variation driving factors of the ES relationships and ESBs in the Altay region from 1990 to 2020 and provided related ecological management suggestions for each ESB.

This research can be concluded as follows: (1) During 1990–2020, there was a consistent pattern in the intensity and trend of changes in water yield and soil retention. Soil erosion has been shown to be one of the most important environmental challenges in the region. The spatial disparities in the four categories of ecosystem services are associated with regional variations in natural geographical environments. (2) The trade-off intensity between water yield and the three other types of ESs is gradually decreasing, indicating a positive trend towards improved ecological quality in the Altay region. (3). The clustering results led to the categorization of the Altay region into four distinct types of ESBs. The internal compositional differences and spatial distribution of ESBs are assigned by the interaction relationships between ESs and landscape types. (4) There is a complex non-linear dynamic in the relationship of the different drivers to the four types of ESBs over different years. Natural conditions and climatic factors emerge as the key ecological elements influencing the spatio-temporal variations in ESBs. In contrast, societal factors (e.g., land expansion for construction and human activity intensity) drive the changes in ecosystem service functionality. Overall, by identifying the specific areas and times where certain ESs are most critical or vulnerable, decision-makers can better allocate resources and prioritize conservation efforts. This targeted approach could lead to more effective

land-use planning, sustainable resource management, and enhanced ecosystem resilience in the face of environmental challenges.

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