

Article

Assessing Trade-Offs and Synergies in Ecosystem Services within the Tianshan Mountainous Region

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Abstract: In managing ecosystem services (ESs), it is vital to understand and effectively regulate the trade-offs and synergies (ToSs) involved. This study investigates the Tianshan Mountains (TSMs), utilizing the InVEST (Integrated Valuation of ESs and Tradeoffs) model to evaluate ecosystem service changes from 2000 to 2020, while employing univariate linear regression to examine their spatiotemporal dynamics. Pearson correlation analysis was also conducted to assess how climatic variables (temperature and precipitation) and vegetation indicators (NDVI, normalized difference vegetation index) influence the overall ecosystem service benefits. The findings reveal notable spatial heterogeneity and dynamic shifts in ESs across the TSMs, with strong synergies observed between carbon storage (CS) and other services (such as habitat quality, HQ; soil conservation, SC; and water yield, WY), especially in areas experiencing increased vegetation. However, the connection between HQ and WY was comparatively weaker and occasionally exhibited negative correlations during specific periods, highlighting the intricate trade-offs among various services. The correlation analysis further showed that climate and vegetation changes significantly impact ecosystem service benefits, with declining precipitation and rising temperatures reducing these benefits, whereas higher NDVI was associated with improved service functions. Ultimately, this study emphasizes the necessity of recognizing and managing ToSs in ESs to promote sustainable regional ecosystem development.



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Keywords: ecosystem services; trade-offs and synergies; climate change; Tianshan mountain; invest model

1. Introduction

Ecosystem services (ESs) refer to the various products and advantages provided by ecosystems, either directly or indirectly, to humans [1–3]. These services include provisioning, regulating, cultural, and supporting functions [4–11], which are essential for human health and well-being [12–14]. However, under escalating global climate change and growing anthropogenic pressures, approximately 60% of ESs globally are declining, with the rate of degradation increasing each year [15–17]. This alarming trend presents significant risks to societal progress and development [18,19]. Thus, it becomes imperative to accurately evaluate and effectively manage ESs while aligning them with socioeconomic development goals to achieve regional sustainability and foster ecological civilization [20–22].

Despite this importance, current studies often struggle with comprehensively evaluating ESs and their trade-offs, particularly in achieving high-resolution, dynamic spatial analyses. Presently, various methods are employed in this field, such as field surveys, ecological modeling, statistical analyses, and remote sensing technology [23–28]. Notably, remote sensing stands out due to its extensive coverage, temporal continuity, and cost-effectiveness [29,30]. Ecosystem service relationships are inherently complex and

multifaceted [31,32]; enhancing certain services may lead to improvements or reductions in others, highlighting the ToSs between them [33,34]. Given these intricate interactions, a quantitative approach to assessing and managing these ToSs is crucial for sustainable ecosystem management [35–37]. Tools such as remote sensing, GIS, ecological models (like InVEST, ARIES, and SWAT), and statistical analyses are commonly used to evaluate these relationships [38–40]. The InVEST model, in particular, is widely adopted for its ability to integrate remote sensing data with ecological theory, providing insights into the spatial distribution and relationships among ESs, and thereby offering a robust foundation for analyzing trade-offs [41–43].

Mountain ecosystems play a crucial role in maintaining regional ecological balance, promoting biodiversity, and supporting human livelihoods [42]. These ecosystems provide various services, including water supply, soil conservation, carbon storage, and habitat for wildlife, all of which directly impact human quality of life and sustainable development. However, as global climate change and human activities intensify, mountain ecosystems are encountering unprecedented challenges [38]. Extreme weather events driven by climate change, such as frequent droughts and heavy rainfall, not only affect the functionality of these ecosystems but also threaten the livelihoods of local residents. Furthermore, urbanization and overexploitation have severely degraded mountain vegetation, further diminishing the ecosystems' resilience and recovery capacity. The necessity of studying mountain ESs is becoming increasingly evident [26,31]. By scientifically assessing the current state and potential value of these services, reliable information can be provided to policymakers, guiding the formulation of regional sustainable development strategies [33]. Additionally, a deeper exploration of the trade-offs between different ESs can aid in optimizing resource allocation and balancing economic development with ecological protection [37]. Particularly in the context of ecological degradation and biodiversity loss, a scientific understanding of the dynamic changes and feedback mechanisms of ESs will provide essential theoretical support for the implementation of restoration and conservation measures. The Tianshan Mountains (TSMs), serving as a vital ecological barrier in northwestern China, are critical for regional and national ecological security [44,45]. Recently, the ecosystems of the TSMs have faced severe challenges such as glacier melting, intensifying droughts due to climate change, vegetation destruction, and biodiversity loss resulting from human activities [46]. Therefore, it is crucial to scientifically assess these services and analyze their trade-offs to develop effective ecological conservation and restoration strategies.

The main objectives of this study are: (1) to quantify the spatiotemporal changes in ESs in the TSMs; (2) to analyze the ToSs among various ESs; and (3) to clarify the effects of climatic and vegetation factors on these services. The findings are intended to provide a scientific foundation for ecosystem service planning in the TSMs, contributing to ecological protection and promoting sustainable development in the region.

2. Materials and Methods

2.1. Study Area

The TSMs, located in the Xinjiang Uygur Autonomous Region of China (39.63°–45.39° N, 73.83°–95.16° E), span central Xinjiang, effectively dividing it into northern and southern parts. This mountain range stretches approximately 2500 km from east to west, encompassing about 24.2% of Xinjiang's area. The elevation ranges from 200 m to a peak of 6803 m, with the gradient gradually decreasing from the central areas toward the periphery. The landscape is predominantly composed of grasslands, cultivated lands, and barren areas (Figure 1). Situated in an arid to semi-arid region, the TSMs experience a temperate continental climate, with an average annual temperature of 1.03 °C and annual precipitation averaging 406.97 mm. Often called the "Water Tower of Central Asia", the TSMs serve as vital water sources for the Ili and Tarim Rivers in China [47–49]. The Tianshan region also hosts rich natural resources and diverse ecosystems, such as forests, grasslands, wetlands, and glaciers, which provide a variety of essential ESs that are crucial for both regional and broader socio-economic development [50–53]. However, these services have

been significantly challenged in recent years. Climate change has led to shrinking glaciers, diminishing water resources, and increased occurrences of extreme weather events [54–56]. Furthermore, intensified human activities, including agricultural expansion, deforestation, and changes in land use, have contributed to a decline in forest cover, placing considerable stress on the regional ecosystems [57–59]. These factors not only diminish the availability of ecosystem services but also complicate the ToSs between them.

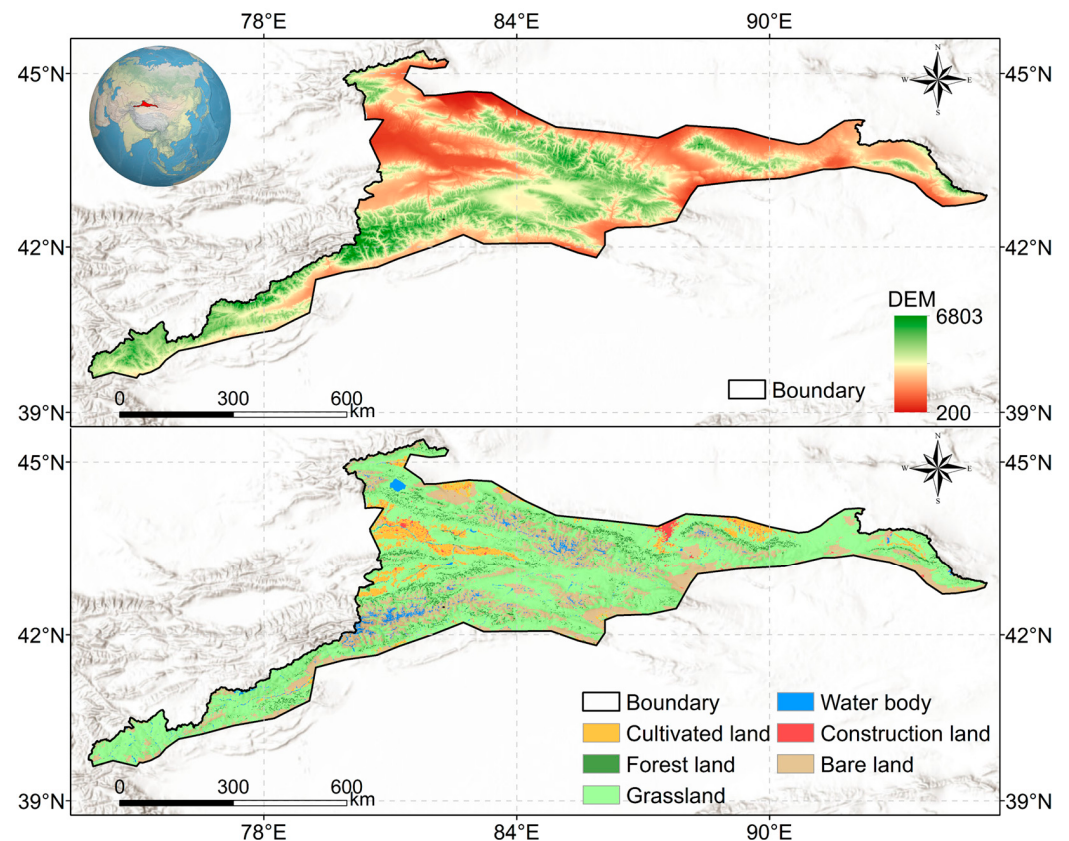


Figure 1. Geographic location of the Tianshan Mountains (TSMs).

2.2. Data Sources

Table 1 provides an overview of the datasets employed in this study along with their sources. All raster data were resampled to a consistent resolution of 1 km.

Table 1. Data name; source description.

Data Name	Scale	Data Source
Land use type	1 km	Resources and Environment Data Center of Chinese Academy of Sciences (https://www.resdc.cn) (accessed on 15 April 2023))
Precipitation	1 km	Earth Resources Data Cloud (http://www.gis5g.com) (accessed on 20 April 2023))
Temperature	1 km	National Tibetan Plateau Data Center (https://data.tpdac.ac.cn) (accessed on 20 April 2023))
Potential evapotranspiration	1 km	Space-time Tripolar Environment Big Data Platform (https://poles.tpdac.ac.cn/zh-hans) (accessed on 17 April 2023))
Digital elevation model	1 km	Geospatial Data Cloud (https://www.gscloud.cn) (accessed on 15 June 2023))
Soil data	1 km	Harmonized World Soil Database (HWSD) (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases) (accessed on 15 May 2023))
Root depth	1 km	Scientific Data (https://www.nature.com/sdata) (accessed on 10 July 2023))
Normalized difference vegetation index	1 km	National Aeronautics and Space Administration (https://search.earthdata.nasa.gov) (accessed on 25 April 2023))

2.3. Methods

2.3.1. ES Assessment

The InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model is notable for its versatility, user-friendliness, scientific rigor, wide applicability, decision support features, regular updates, visual outputs, and open-source framework, enhancing its reliability and broader applicability compared to other models [60]. In this study, the InVEST model was employed to evaluate carbon storage (CS), water yield (WY), soil conservation (SC), and habitat quality (HQ) in the Tianshan region from 2000 to 2020. CS is essential for climate regulation services and serves as a key indicator of regional ecosystem functionality [61,62]. Enhancing the CS capacity of terrestrial ecosystems has become a vital scientific and technological priority in addressing global climate change [63]. Moreover, the degradation and loss of natural habitats is a leading cause of biodiversity decline, with HQ serving as a critical metric for assessing the environment's capacity to support the survival and reproduction of species [64]. WY, particularly in arid and semi-arid regions, is another essential ecosystem service, vital for agriculture, industry, hydropower, recreation, and the sustainable development of ESs [65]. Lastly, SC is a significant regulatory service, and assessing its supply and demand is critical for effective watershed management [66,67]. The detailed calculation process for each ecosystem service indicator is illustrated in Figure 2.

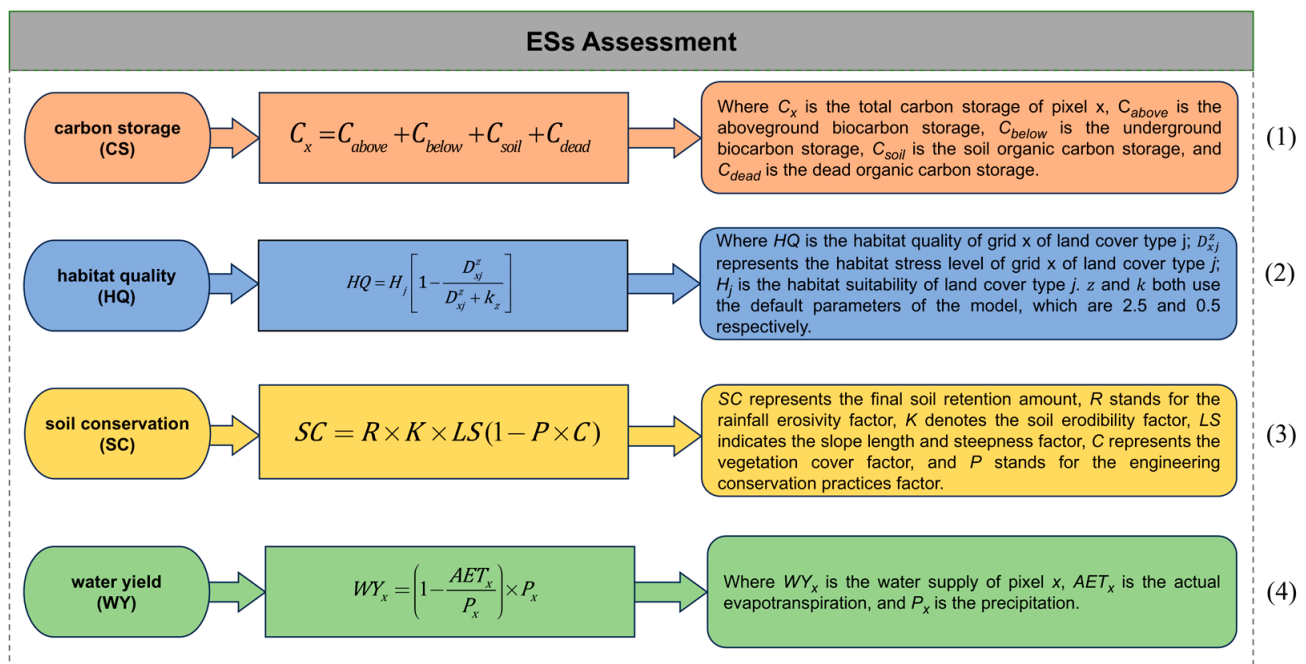


Figure 2. ES assessment methodology.

2.3.2. Trend Analysis of ESs

Univariate linear regression trend analysis is a method used to identify and analyze trends in time series data through a single-variable linear regression model [68]. This approach is effective for detecting linear trends in how an independent variable affects a dependent variable, as well as for predicting and assessing data behavior over time. It helps determine whether a significant upward or downward trend is present. The specific formula is as follows:

$$\theta_{slope} = \frac{n \times \sum_{i=1}^n (i \times B_i) - \sum_{i=1}^n i \sum_{i=1}^n B_i}{n \times \sum_{i=1}^n i^2 - (\sum_{i=1}^n B_i)^2} \quad (1)$$

In this formula, θ_{slope} represents the trend slope, B_i denotes the sample value for year i , and n indicates the length of the study period. A positive θ_{slope} implies that the sample

value gradually increases over time, while a negative θ_{slope} indicates a gradual decrease. If θ_{slope} is zero, it suggests that the sample value remains constant throughout the study period, showing no clear trend.

2.3.3. Analysis of Ecosystem Service ToSs

In ecosystem service studies, analyzing ToSs is essential to understanding the interactions between different services [69]. The Spearman analysis is a nonparametric statistical method that measures the strength and direction of a monotonic relationship between two variables [70]. Due to its adaptability to nonlinear and non-normally distributed data, Spearman correlation analysis is commonly used to assess these relationships [71]. The specific formulas are as follows:

$$O_V(X_i - Y_i) = 1 - \frac{6 \sum_{i=1}^n (P_i - Q_i)^2}{n(n^2 - 1)} \quad (2)$$

Here, P_i represents the rank of X_i in the sequence $\{(X_i)\}$, and Q_i denotes the rank of Y_i . A positive O_V indicates a synergistic relationship between two ESs, while a negative O_V suggests a trade-off. If O_V is close to zero or statistically insignificant, it indicates an independent relationship between the two services.

2.3.4. Standardization of ESs

Standardizing ESs entails the dimensionless scaling or uniform transformation of quantitative results across different services to facilitate a more scientific and comparable analysis [72]. Due to varying units and magnitudes, direct comparisons can be misleading. Standardization allows these services to be evaluated on a consistent scale, thereby enhancing the accuracy and comparability of results. The specific formulas are as follows:

$$X_i' = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (3)$$

where X_i' is the standardized class i ecosystem service, X_{min} and X_{max} are the minimum and maximum values of the class, respectively, and X is the original value.

2.3.5. Overall Benefits of ESs

Integrated benefit assessments of ESs quantify and standardize the overall value of multiple ESs, considering their interconnections and mutual reinforcement [73]. When analyzing relationships among various services, integrated assessments are crucial for evaluating their combined benefits [74]. This approach provides a scientific foundation for environmental management, policy-making, and land-use planning, aiding in harmonizing ecological conservation with economic development. The specific formulas are as follows:

$$ES_{OB} = \frac{1}{n} \sum_{i=1}^n X_i' \quad (4)$$

Here, ES_{OB} represents the integrated benefits of ESs, and X_i' represents the standardized value of the i th ecosystem service. The variable n refers to the number of ecosystem service types, which in this study is Equation (4).

2.3.6. Analysis of Factors Influencing ESs

In this study, the Pearson correlation coefficient was used to analyze the factors influencing ESs by measuring the linear correlation between ecosystem service indicators and potential influencing factors [75]. The specific formula is as follows:

$$r_{x,y} = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}} \quad (5)$$

Here, $r_{x,y}$ represents the correlation coefficient between variables x and y . The variable x_i is the composite benefit in year i , and y_i represents the value of an influencing factor in year i . The symbols $\bar{x}$ and $\bar{y}$ denote the average values of the composite benefit and the influencing factor, respectively.

3. Results

3.1. Spatial and Temporal Changes in ESs

Between 2000 and 2020, the ESs in the Tianshan region underwent significant changes, displaying distinct temporal dynamics (Table 2). CS services exhibited an overall upward trend, with an initial increase from 2000 to 2010, followed by a slight decline from 2010 to 2020. HQ continuously decreased, dropping from 0.58 in 2000 to 0.54 in 2020. SC peaked at 20.65 (10^3 t) in 2010 but declined significantly to 15.57 (10^3 t) by 2020. WY services exhibited fluctuating changes, reaching a maximum of 55.12 mm in 2010 and decreasing to 37.51 mm in 2020. These trends reflect the dynamic adjustments of the Tianshan region's ESs in response to climate change and human activities. The CS services are closely related to the vegetation condition of the vertical natural zones in the study area, whereas accelerated urbanization leads to a downward trend in CS. The decrease in HQ is likely closely related to land-use changes, while the fluctuations in SC reflect the intensifying issue of soil erosion. The variations in WY services reveal the impact of fluctuating precipitation on regional water resources. These changes underscore the complexity of the Tianshan region's ESs and the intricate interactions within the ecosystem.

Table 2. Temporal changes in ESs in the Tianshan Mountains (TSMs).

	CS (10^2 t)	HQ	SC (10^3 t)	WY (mm)
2000	95.86	0.58	19.48	44.58
2010	99	0.55	20.65	55.12
2020	98.48	0.54	15.57	37.51

From 2000 to 2020, the ESs in the TSMs underwent significant spatial changes, exhibiting varying degrees of spatial heterogeneity across different regions (Figure 3). CS services remained relatively stable in most areas, although there was a slight decline in CS capacity in parts of the central, western, and southern regions, likely linked to changes in land use or a reduction in vegetation cover. HQ experienced a slight overall decline, particularly in the central and southern regions, where a noticeable deterioration in HQ was observed. SC showed complex patterns of change, with a significant decrease in SC capacity in the western and southern regions after 2010, reflecting an increasing trend of soil erosion. WY services exhibited considerable volatility, with a marked decline in WY in the southern and western regions after 2010, potentially influenced by reduced precipitation or changes in water resource management.

3.2. Ecosystem Service ToSs

During the period from 2000 to 2020, the ESs in the TSMs were predominantly characterized by significant synergies, particularly between CS and HQ, SC, and WY services (Figure 4). The synergistic effects between CS and other services were the most pronounced, especially in 2020, when the positive correlation between CS and HQ reached its peak, suggesting that increased vegetation cover not only enhanced CS but also improved HQ and SC functions. Additionally, a strong synergy was observed between SC and WY services, indicating that soil and water conservation measures contribute to improved water conservation. However, the relationship between HQ and WY services was relatively weak, and even showed a slight negative correlation in 2020, possibly reflecting the competitive impact of increased vegetation on water resources. Overall, the ESs in the TSMs were predominantly synergistic, particularly between CS and other services, but management strategies should be mindful of the potential trade-offs between HQ and WY.

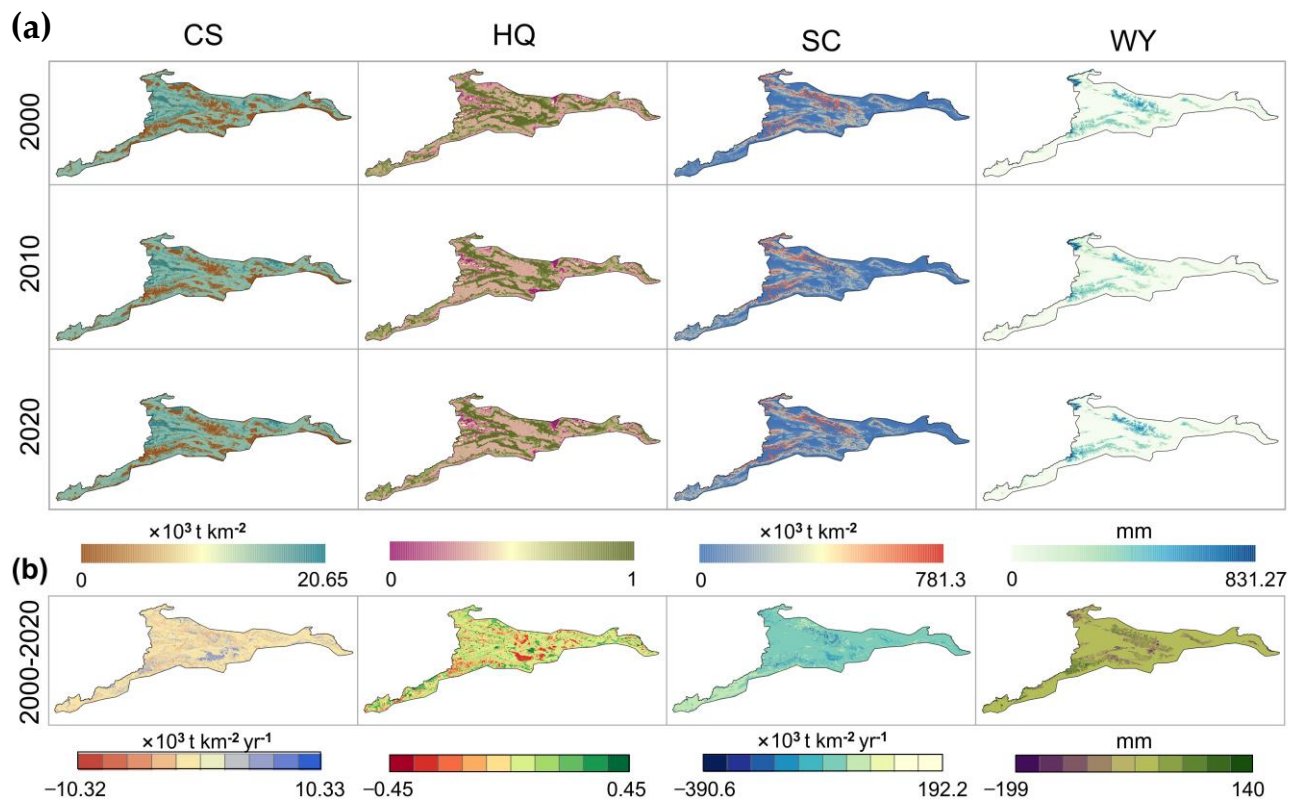


Figure 3. Spatial distribution of the ESs in the Tianshan Mountains (TSMs), where (a) represents the spatial distribution of the Tianshan Mountains from 2000 to 2020, and (b) represents the spatial change trend. CS represents carbon storage services, HQ represents habitat quality, SC represents soil conservation, and WY represents water yield services.

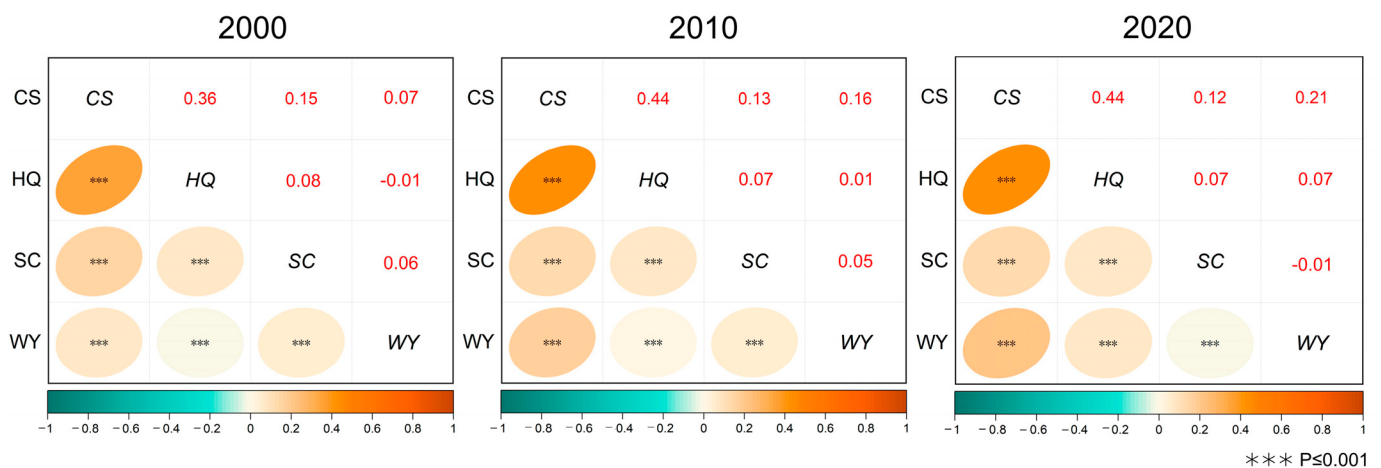


Figure 4. Ecosystem service trade-off and synergy relationships in the mountainous regions of the Tianshan Mountains (TSMs). CS for carbon storage services, HQ for habitat quality, SC for soil conservation, and WY for water yield services.

3.3. Changes in the Overall Benefits of ESs

The spatial distribution of comprehensive ES benefits in the TSMs showed significant dynamic changes from 2000 to 2020 (Figure 5). Overall, the comprehensive benefits exhibited slight fluctuations over these 20 years, with the spatial distribution expanding gradually from the central and southern regions toward the northern and western regions. In 2000, the central part of the TSMs had higher comprehensive benefits, particularly in river valleys and areas with good vegetation cover, with ecosystem service benefit values

ranging from 0.37 to 0.48. By 2010, the comprehensive benefits in the central and southern regions had increased, while the benefits in the northern and western regions slightly declined. By 2020, the overall trend showed an expansion of comprehensive benefits toward the northern and western regions, with a decrease in benefits in the southern region. Despite changes in the overall distribution pattern, the central region maintained relatively high comprehensive benefits. These spatial changes in comprehensive benefits reflect the TSMs' ecosystem responses to climate change and human activities at different times, revealing dynamic changes in ecosystem service functions across different geographic locations within the region.

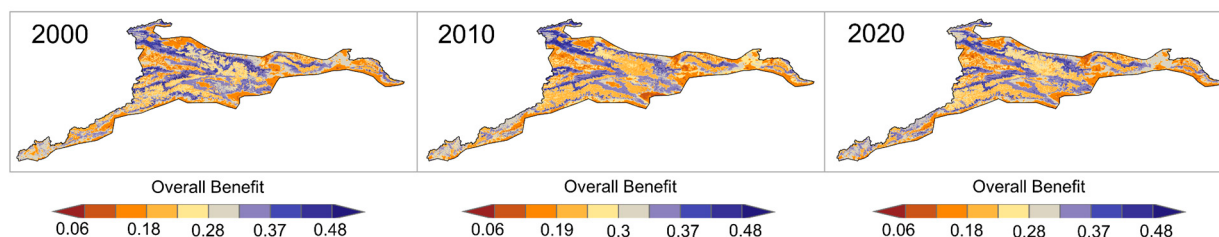


Figure 5. Changes in the comprehensive benefits of ESs in the mountainous regions of the Tianshan.

4. Discussion

4.1. Impacts of Climate Change on ESs

As a critical ecological barrier for Xinjiang and China as a whole [76,77], the TSMs' ESs are profoundly affected by climate change from multiple perspectives. Correlation analyses between temperature, precipitation, and the comprehensive benefits of ESs in the TSMs (Figure 6) indicate that precipitation plays a crucial role in maintaining the stability of ESs. However, the impact of climate change on WY services is dual-faceted [78]. With rising temperatures in arid regions, glacier melt accelerates, temporarily increasing river runoff and providing a certain degree of assurance for the regional water supply [79,80]. Nonetheless, the long-term retreat of glaciers in the TSMs will lead to future uncertainties in water supply, particularly under increasingly uneven temporal and spatial distribution of precipitation, which will further exacerbate the instability of WY services. Similarly, CS services exhibit complex response patterns to climate change. In some areas, rising temperatures have promoted vegetation growth, enhancing vegetation's CS capacity [81], but frequent extreme climate events, such as droughts and heavy rainfall, may cause vegetation degradation [82], weakening this positive effect.

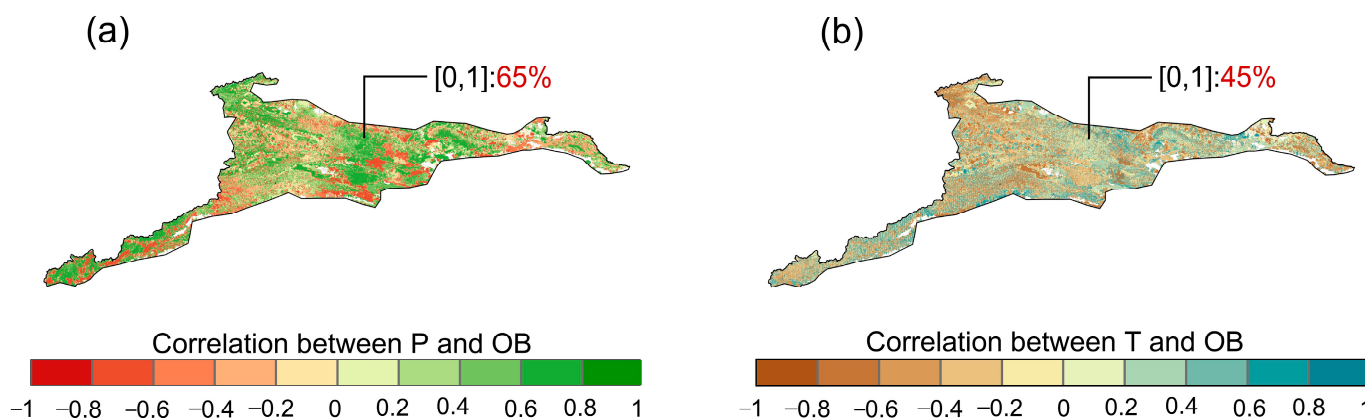


Figure 6. Correlation between the overall benefits of ESs and T (temperature) and P (precipitation) in the mountainous areas of the Tianshan Mountains (TSMs), where (a) denotes the correlation of precipitation with OB and (b) denotes the correlation of temperature with OB. Parentheses indicate the percentage of positively correlated areas in the region.

Meanwhile, climate change also significantly impacts HQ and SC services. Changes in temperature and precipitation patterns may reduce the suitable habitats for certain species, threatening biodiversity [83], especially for species sensitive to temperature and humidity. Moreover, changes in vegetation types could lead to adjustments in land use, affecting HQ, resulting in habitat fragmentation and degradation, and weakening ecosystem stability and biodiversity support capabilities. In terms of SC, the increased intensity of precipitation and changes in vegetation cover brought about by climate change, especially in areas with relatively steep slopes, may exacerbate the risk of soil erosion [84,85]. Heavy rainfall can easily trigger surface runoff, leading to soil loss, while the increase in evaporation caused by rising temperatures may reduce soil moisture, weakening soil water conservation capacity and structural stability. Therefore, climate change presents severe challenges to the ESs of the TSMs, but it also provides opportunities for research and the implementation of measures to enhance ecosystem resilience.

4.2. Impact of Vegetation Change on ESs

The normalized difference vegetation index (NDVI) is a key indicator of vegetation health and growth status, effectively reflecting regional vegetation trends [86,87]. In recent years, due to global warming and intensified human activities, NDVI values in the TSMs have exhibited noticeable fluctuations. The positive correlation between NDVI and OB covers roughly 50% of the area, primarily in regions with high vegetation cover (Figure 7), suggesting strong ES capacity in these areas. Increased NDVI typically indicates better vegetation cover, which can enhance ESs such as WY, SC, and CS [88,89]. However, the relationship between NDVI and ESs is not always straightforward. Under extreme climatic conditions, even if NDVI increases, shifts in plant species or differences in growth cycles may result in reduced ES benefits.

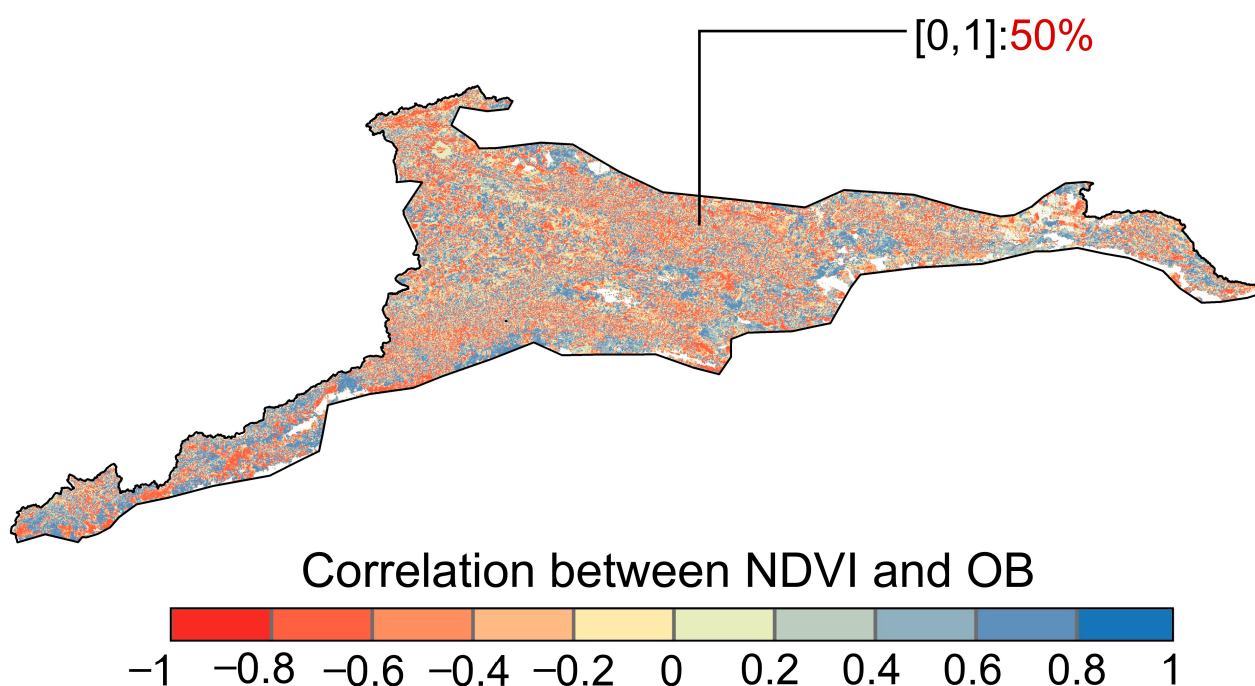


Figure 7. Correlation between the integrated benefits of ESs and NDVI in the Tianshan Mountains (TSMs), where parentheses indicate the percentage of positively correlated areas within the region.

Research on the TSMs indicates that the correlation between NDVI and ESs exhibits strong spatial heterogeneity, consistent with findings in other regions [90,91]. This heterogeneity is primarily due to variations in topography, climate, and human activities [92]. In more humid areas, an increase in NDVI is typically accompanied by a significant enhancement in ESs due to higher vegetation diversity and stronger ecosystem stability. In contrast,

in drier areas, NDVI shows greater variability, with vegetation cover more susceptible to climate change, resulting in relatively limited improvements in ESs [93]. Moreover, human activities such as overgrazing and inappropriate land use may lead to NDVI increases while simultaneously causing degradation in ES functions [94]. This phenomenon suggests that vegetation changes in the TSMs not only affect local ESs but also have profound impacts on the stability of ecosystems across the entire watershed. Therefore, future ecological management and restoration strategies should fully consider the spatial heterogeneity of NDVI changes and formulate corresponding management measures to maximize the comprehensive benefits of ESs.

4.3. ToSs between ESs

In studying ESs in the TSMs, the four services—WY, CS, HQ, and SC—primarily exhibit synergistic relationships (Figure 4). This synergy implies that as one service improves, others tend to enhance simultaneously [95,96]. For instance, an increase in CS capacity is often associated with enhancements in HQ and SC [97], likely due to improved vegetation cover. This not only boosts CS but also enhances soil stability, reduces erosion, and creates better habitats for wildlife [98]. Moreover, WY also benefits from improved vegetation, as stable soil conditions help conserve and transport water more effectively [99]. The observed synergies among these services provide an essential foundation for integrated ecosystem management and conservation efforts in the TSMs, aiming to maximize ecosystem functionality.

When compared to other regions, the synergistic effects among ESs in the TSMs share both similarities and notable differences. In humid regions of southern China, such as the Yangtze River Basin, synergies between ESs, especially in water conservation and habitat quality, are also prominent. The abundant precipitation and biodiversity in these areas contribute to strengthen the positive feedback among ESs. In contrast, in the arid regions of northern China, the semi-arid environment of the TSMs promotes more evident synergies among WY, CS, and SC, primarily due to moderate vegetation recovery.

In regions like the Inner Mongolia grasslands, excessive vegetation recovery can result in trade-offs among ESs, differing from the TSMs, where moderate vegetation recovery benefits both water conservation and WY services. Additionally, the TSMs' relatively low human interference and more natural ecological state contribute to favorable conditions for positive interactions among ESs. Thus, while the ToSs among ESs in the TSMs align with findings from other studies, they also reflect the distinct ecological context and management practices of the region, underscoring the importance of regional characteristics in shaping ES interactions in various contexts.

5. Conclusions

This study utilized the InVEST model to assess ESs in the TSMs from 2000 to 2020 and analyzed their trends using univariate linear regression. The findings revealed significant spatial heterogeneity in the ESs of the TSMs, with varying ToSs over time and across regions. Spearman's correlation analysis was conducted to evaluate these ToSs, showing that CS, HQ, SC, and WY generally exhibited synergistic relationships, with the strongest synergies between CS and the other services. As vegetation cover increased, enhancements in CS, SC, and HQ were evident. However, the relationship between HQ and WY was weaker in certain areas and even showed a slight negative correlation in some years, reflecting the complex and sometimes contradictory responses of ESs to climate change and land-use dynamics.

Additionally, the Pearson correlation analysis highlighted significant associations between climatic factors (temperature and precipitation), vegetation factors (NDVI), and the comprehensive benefits of ESs. The results showed that variations in temperature and precipitation significantly affected the overall ecosystem service benefits, with decreased precipitation causing a notable decline and increasing temperatures worsening this impact. In contrast, a rise in NDVI was positively associated with enhanced ecosystem service

benefits, highlighting the importance of vegetation cover in improving these functions. However, certain limitations should be acknowledged. The InVEST model assessment in this study focused on four ESs, excluding cultural services, and relied on subjective parameter settings due to the lack of measured data. Parameters had to be inferred from areas with similar environmental conditions, leading to some degree of bias in model accuracy. In future research, incorporating measured data from the study area would help provide a more accurate reflection of local ecological conditions.

In conclusion, while the results may not fully capture the actual conditions of ESs in the study area, they successfully reveal trends across different services and provide a scientific reference for the sustainable development of the TSMs and for formulating ecological management policies.

Author Contributions: H.L. was responsible for conceptualization, methodology, validation, formal analysis, investigation, and resource management, as well as preparing the original draft and overseeing the writing process. S.C. contributed to software development and data curation, while also providing supervision. H.Z. offered additional supervision. C.Z. handled project administration and funding acquisition. All authors have read and agreed to the published version of the manuscript.

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