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Change and Tradeoff/Synergy Analysis of Watershed Ecosystem Services: A Case Study of Qinghai Lake Basin

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Abstract: Understanding the tradeoffs/synergies between ecosystems is crucial to effective watershed ecosystem management and sustainable development. In this study, the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) and Carnegie Ames Stanford Approach (CASA) models were utilized to estimate four ecosystem services (ESs), including water conservation capacity, soil retention, habitat quality, and carbon storage services, in Qinghai Lake Basin between 2000 and 2018. Local Indicators of Spatial Association (LISA) and tradeoffs/synergies criterion (TSC) were used to reveal the relationships between the ESs. The results show that the water conservation capacity, soil retention, habitat quality, and carbon storage service in Qinghai Lake Basin all increased between 2000 and 2018. TSC and LISA revealed that carbon storage and habitat quality, habitat quality and water conservation capacity, and carbon storage and soil retention had the same relationship, as did habitat quality and soil retention. In addition, LISA showed that the relationships between ESs are mainly based on high high clusters that concentrate in the middle of the basin. The analysis also revealed obvious spatial heterogeneity. This study aims to compensate the research deficiencies that affected previous studies of the Qinghai Lake Basin and provide a point of reference for the sustainable development of the basin.

Keywords: Qinghai Lake Basin; ecosystem services; LISA; tradeoff; synergy

Citation: Wu, X.; Zhang, L.; Gao, L.; Li, Y.; Liu, X. Change and Tradeoff/Synergy Analysis of Watershed Ecosystem Services: A Case Study of Qinghai Lake Basin. *Sustainability* **2023**, *15*, 11711. https://doi.org/10.3390/su151511711

Academic Editor: Jan Hopmans

Received: 26 June 2023
Revised: 24 July 2023
Accepted: 27 July 2023
Published: 28 July 2023

1. Introduction

Ecosystem services refers to the benefits derived from the ecosystem and ecological processes that maintain human life [1,2]. The United Nations Millennium Ecosystem Assessment divided this concept into four categories: provision services, regulation services, support services, and cultural services [3,4]. The interaction between ESs allows them to affect each other, mainly by simultaneously increasing them (synergy) or creating a relationship in which one service increases when another service decreases(tradeoff) [5,6]. According to research, ecosystems can create GDP 15 trillion of value for humans, though under the influence of human activities, they have lost two-thirds of their value [7]. It is urgent that we analyze the relationship between ESs, as this process can provide an essential basis for formulating ecological protection programs. Richards et al. [8] analyzed tradeoff/synergy relationships in tropical urban coastal areas based on Pareto curves and found that only carbon storage and charcoal production, as well as charcoal production and recreational accessibility, showed trade-offs. Wang et al. [9] studied the relationships between ESs in four climatic regions (arid, semi-arid, plateau, and semi-humid climate zones) on the Loess Plateau, finding that in different climatic regions, the relationships between same ESs are different. Luo et al. [5] explored the tradeoff/synergy relationship in Nanliujiang River Basin, and their results show synergy between carbon storage and soil conservation. But, in the Gansu Qinghai section of the Yellow River Basin, the relationship between carbon storage and soil conservation is viewed as a tradeoff [10]. Therefore, in different places and climatic regions, the relationships between the same ESs are different.

The Qinghai Tibet Plateau (QTP) is the priority area for ES trend analysis, as it exhibits high sensitivity to global warming and plays a pivotal role in upholding regional and global ecological security [11]. The Qinghai Lake Basin is located in the northeastern part of the QTP, and it is an important region for the maintenance of ecological balance in the northeastern part of the QTP and clearly impacted by global climate change [12]. Watersheds are not only the focus of research into complex issues, such as regional ecological, economic, and social development, but also one of the main research objects of earth system science [13]. Currently, China's watershed-scale ecological and environmental monitoring network is not complete, and its results are scattered; thus, it is urgent to focus on systematic and comprehensive research. The ecological system of the Qinghai Lake Basin largely reflects the overall ecological changes in the QTP. The assessment of ESs in the Qinghai Lake Basin is conducive to understanding the health of ecosystem functions in the Qinghai Lake Basin, and it can also serve as a reference for the improvement of the ecological environment in the Qinghai Lake Basin.

In the Qinghai Lake Basin, Qi et al. [14] explored the impact of human activities on ESs. Han et al. [15] evaluated the impact of land use change on habitat quality (HQ) in the Qinghai Lake Basin, and their study indicated that changes in land use were the primary factor that contributed to climatic changes. Liu et al. [16] used the localized modified InVEST model and geographical detector method to simulate the basin water production service and evaluate the spatial differentiation characteristics of water yield. The study of ecosystem services involved the forest, farmland, grassland, and wetland, whereas in previous studies that considered the Qinghai Lake Basin, scholars mostly focused on the changes in a single ecosystem service, such as water yield or soil erosion. No reports that discuss tradeoff and synergy relationships between ESs in the Qinghai Lake Basin exist.

At present, the relationship between ESs has become a hot topic in ecosystem service research, and quantitative assessment of ecosystem services and their trade-offs/synergies is an important component of ecosystem services research and a prerequisite for effective ecosystem management and decision-making [17]. Research methods [18], driving mechanisms [19], and spatial scales [20,21] related to ecosystem service tradeoff synergy relationships have been thoroughly investigated by Chinese and international scholars. Liu et al. [22] simulated the value of ecosystem service functions in Xinjiang in different contexts based on a Bayesian network model. Zhu et al. [23] quantitatively assessed the supply demand matching relationships between ESs in the Bailong River watershed in Gansu using the InVest and supply demand ratio coordination degree models. Lin et al. [24] simulated land use and predicted ES outcomes for 2030 in the Guangdong Hong Kong Macao Greater Bay Area based on the InVest and GeoSOS-FLUS models. Among the various research methods used, the ecological modeling approach can best reveal the spatial heterogeneity of services based on ecological processes and mechanisms. Therefore, in this paper, we used the Integrated Valuation of Ecosystem Services and Tradeoffs (InVest) and Carnegie Ames Stanford Approach (CASA) models to calculate ecosystem services.

Zheng et al. [25] quantitatively assessed the ESs of Sanjiangyuan National Park between 1990 and 2015 based on the equivalent factor method, spatial autocorrelation, and correlation coefficients. Aryal et al. [26] considered the case of multifunctional landscape in the Hindu Kush Himalayan region, and Garrett Mean Scores (GMS), ordinal logistic regression estimates, and Chi-square tests were used to assess quantitative data. Wu et al. [27] applied the root mean square error (RMSE) method to identify the relationships between ESs. These scholars analyzed the tradeoff/synergy relationships through traditional statistical methods, scenario analysis method, and model simulation, though these methods cannot spatially express the trade-off/synergy relationship; thus, this paper used the Tradeoff/Synergy Criterion (TSC) to depict the tradeoff/synergy relationships within the watershed, while TSC depicted the relationship between ESs in spatial terms, which helped us to better understand them. Local Indicators of Spatial Association (LISA) were also used to identify the relationships between ESs. In this paper, we used two methods to explore the tradeoff/synergy relationships in the Qinghai Lake Basin, which can depicted these relationships in more scientific terms.

This paper quantitatively assessed four ESs in the Qinghai Lake Basin, including soil retention (SC) and habitat quality (HQ), based on the InVest model, and the carbon storage (NEP) and water conservation capacities (WR) were calculated using the CASA model, which provided a point of reference to enable positive ecological management in the Qinghai Lake Basin. LISA and TSC were used to analyzed the tradeoff/synergy relationships in Qinghai Lake Basin between 2000 and 2018, and this approach aimed to compensate for research deficiencies in previous studies of the Qinghai Lake Basin and provide a point of reference for the sustainable development of the basin.

2. Materials and Methods

2.1. Study Area

The Qinghai Lake Basin, which is the biggest endothermic lake in China, is located in northeastern Qinghai, China. It is surrounded by mountains on all sides and located at the intersection of the northwest arid, southwest alpine, and eastern monsoon zones [28]. Elevation is in the range 3159–5279 m (Figure 1), with high topography in the northwestern area and low topography in the southeastern area. Average annual precipitation ranges from 304.31 to 605.14 mm, and the average multi-year temperature ranges from −9.27 to 2.77 °C. Vegetation types include plentiful and covering grassland vegetation, scrub vegetation, alpine sparse vegetation, desert vegetation, and meadows [29,30].

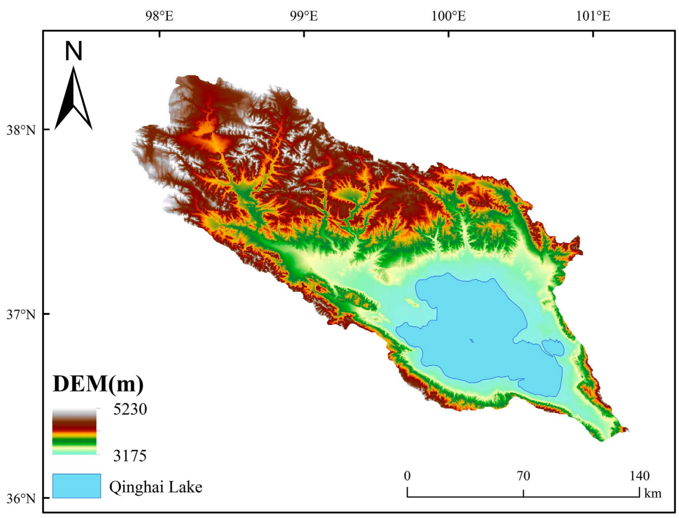

Figure 1. Digital Elevation Model of the Qinghai Lake Basin.

2.2. Data Sources

Normalized Difference Vegetation Index (NDVI) data were obtained through the MOD13Q1 (16-day synthetic MODIS vegetation index product), which were provided by NASA, at a resolution of 250 m. The Qinghai Lake Basin month data in the period 2000–2018 (in which January 2000 data were replaced by January 2001 data) were selected for projection (defined as WGS 1984 UTM 47N) and pre-possessing.

The climate data (radiation, temperature, precipitation) were obtained from the National Tibetan Plateau Science Data Center (https://www.tpdc.ac.cn, accessed on 26 December 2022) of the China Regional Surface Meteorological Elements Driving Dataset (1979–2018) [31]. The China Regional Surface Meteorological Elements Driving Data were organized in NETCDF format and had a temporal resolution. The horizontal resolution was 0.1°, and the time resolution was 3 h. In this paper, the monthly data of Qinghai Lake Basin that denoted the period between 1990 and 2018 in the two datasets were selected and extracted as tiff files using Matlab, and they were projected and resampled at a 250-m resolution.

The LULC data were obtained from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/, accessed on 30 April 2023), and the Chinese land use remote sensing monitoring data for 2000, 2005, 2010, 2015, and 2018 were selected and processed using ArcGIS for projection, resampling, and reclassification (classification according to the CASA model's data requirements) to acquire five phases of land use data related to the Qinghai Lake Basin.

The soil data were obtained from the Chinese soil data set compiled in the World Soil Database (HWSD) at a resolution of 1 km, and they were projected and resampled at a 250-m resolution.

The Digital Elevation Model (90 m) was obtained via the Geospatial Data Cloud (https://www.gscloud.cn/, accessed on 30 April 2023), and the slope data were calculated via ArcGIS based on the DEM data.

2.3. Methods

In this paper, two ecosystem services—soil retention and habitat quality—were calculated based on the InVest model. The Net Ecosystem Productivity (NEP) of vegetation and the Water Conservation Capacity Index (WR) were calculated based on NPP as a carbon storage and water conservation services, which were calculated via the CASA model.

2.3.1. Soil Retention

The Sediment Transport Ratio Model (SDR model) was calculated via the InVest model, which incorporated the plot's ability to intercept upstream sediment based on the general soil loss equation [32], resulting in more scientifically sound calculation outcomes. The calculation equation used was structured as follows:

$$RKLS = R \times K \times LS \tag{1}$$

$$USLE = R \times K \times LS \times P \times C \tag{2}$$

$$SD = RKLS - USLE \tag{3}$$

RKLS represents the total potential soil erosion per raster unit of the current land use type without the correction of *C* and *P* factors, which can be regarded as the soil erosion of bare land; *USLE* represents the total potential soil erosion per raster unit of the current land use type; *SD* represents the plant's contribution to erosion avoidance; *R* represents the rainfall erosion factor, which was calculated using the mean monthly precipitation data; *K* represents the soil corruptibility situation, which was calculated based on the fields of T_clay, T_sand, T_silt, and T_oc; *LS* represents the slope factor and the length factor, which the InVest model calculated via the DEM; *C* represents the vegetation cover factor was calculated based on FVC (Fractional Vegetation Cover); and *P* represents is the soil conservation measure factor.

2.3.2. Habitat Quality

The InVest model habitat quality module portrayed regional habitat quality by establishing a link between land use data and threat factors. The calculation formula used was structured as follows:

$$Q_{xj} = H_j(1 - (\frac{D_{xj}^2}{D_{xj}^2 + k^z})) \tag{4}$$

Q_{xj} is the habitat quality of land class j in x raster; H_j is the habitat suitability of land class j; z is the default parameter of the model, which is usually set at 2.5; and k is the half-saturation constant, which needs to run the model twice (it first set at 0.5 and later set at the half of the maximum value of habitat degradation).

2.3.3. Carbon Storage

Net Ecosystem Productivity (NEP) quantitatively describes the capacity of terrestrial ecosystems to sink carbon sources, and it was calculated based on the difference between vegetation Net Primary Productivity (NPP) and soil microbial respiration (RH) [33]. The calculation equation used was structured as follows:

$$NEP = NPP - RH \tag{5}$$

$$RH = 0.22 \times (\mathrm{e}(0.0913T) + \ln(0.3145R + 1)) \times 30 \times 46.5\% \tag{6}$$

NEP is the net ecosystem productivity of vegetation ($\mathrm{gC/m^2 \cdot a^{-1}}$); NPP is the net primary productivity of vegetation ($\mathrm{gC/m^2 \cdot a^{-1}}$), which was estimated via the CASA model and the detailed calculation formula referred to by Zhu et al. [34]; and RH is soiling microbial respiration ($\mathrm{gC/m^2 \cdot a^{-1}}$), which was calculated via the regression equation of multi-year average temperature and multi-year average precipitation [35].

2.3.4. Water Conservation Capacity

Currently, the main assessment methods used for ecosystem service functions are the model assessment and the quantitative Net Primary Productivity (NPP) indicator assessment methods, though model assessment had high data requirements; thus, the quantitative NPP assessment method was chosen in this paper [36]:

$$WR = NPP_{mean} \times F_{sic} \times F_{\mathrm{pre}} \times (1 - F_{slope}) \tag{7}$$

WR is the ecosystem Water Conservation Capacity Index, NPP_{mean} is the multi-year average net primary productivity of vegetation (19 years NPP were estimated via the CASA model), and F_{pre} is the multi-year average precipitation factor. F_{sic} is the soil infiltration factor, which was calculated based on the T_USDA_TEX field in HWSD. The data were determined using extreme difference normalization, and the ecosystem water conservation capacity index was obtained.

2.3.5. Quantitative Measurements of Tradeoffs and Synergies between Ecosystem Services

Xue et al. [37] proposed a method for delineating differences between ecosystem services to reveal tradeoffs and synergies between ecosystem services, and this method can also present spatial information on tradeoffs and synergies between ecosystem services:

$$TSC = \frac{ES_{i_1 t_2} - ES_{i_1 t_1}}{ES_{j_1 t_2} - ES_{j_1 t_1}} \tag{8}$$

TSC represents the tradeoff/synergy criterion, and ES_{i1t2} and ES_{i1t1} represent classes i and j ES at time periods t_2 and t_1, respectively. If $TSC > 0$, it is clear that the pair Es_i and ES_j vary in the same direction and have a synergetic relationship; otherwise, they have a trade-off-based relationship.

The Tradeoff-Synergy Index (TSI) is used to measure the tradeoff/synergy relationships between ESs [37]:

$$TSI = 1 - \left| |\Delta ES_i| - |\Delta ES_j| \right| \tag{9}$$

ES_i and ES_j are the differences between the ecosystem service values of class i and class j during two periods, i.e., $TSI \in [0, 1]$. A larger TSI value indicated a stronger tradeoff- or synergy-based relationship between the two ecosystem services. All ecosystem services were normalized to remove the effects of different magnitudes before performing *TSI* calculations.

2.3.6. Local Indicators of Spatial Association

Spatial autocorrelation contained both global autocorrelation (Moran *I*), which described the overall characteristics of the space, and Local Indicators of Spatial Association (LISA), which were used to identify local clusters and spatial outliers. In this paper, we used the LISA to identify tradeoff–synergy relationships. The two types of bivariate local spatial autocorrelation results, i.e., high–high and low–low clusters, are described as synergy relationships; high–low and low–high clusters are described as tradeoff relationships. The four clusters mentioned above were significant at $p \leq 0.05$; insignificant results were not considered to have significant tradeoff–synergy relationships [38]. In this study, a 1 km × 1 km fishing network was created, and ecosystem service data were assigned to a vector grid imported into GeoDa for LISA. LISA can show the spatial heterogeneity among ESs in the Qinghai Lake Basin and provide a point of reference for the tradeoffs and synergies between ecosystem services in Qinghai Lake Basin.

3. Results

3.1. Spatiotemporal Variation in Ecosystem Services

The results of the spatial distribution of ESs in the Qinghai Lake Basin between 2000 and 2018 were calculated based on the InVest and CASA models (Figure 2). The water conservation capacity (WR) of the basin was high. Between 2000 and 2008, WR high-value areas were distributed in most parts of the basin, and the low-value areas were sporadically distributed in the central part of the basin. However, there was a decrease of 0.7% in the range between 0.8 and 1, while other ranges increased. The soil retention (SC) low-value areas were distributed around the perimeter of Qinghai Lake and the northwestern part of the basin, while the high-value areas were concentrated in the central part of the basin and the northern area. The high-value area (>3000 t) increased in size by 13.4%, with the annual growth rate being 130.80 t/a. Carbon storage (NEP) showed a trend of gradual increase from the northwest to the southeast, rising from 157.93 gC/m^2 in 2000 to 188.90 gC/m^2 in 2018, indicating a total growth rate of 19.6%. The average annual growth rate was 1.63 $gC/m^2 \cdot a^{-1}$. The area of NEP that was >300 gC/m^2 has increased by 21.7% over the past 19 years. The high-value areas of NEP in 2000 were mainly concentrated in the northern area of Qinghai Lake. In 2018, NEP high-value areas were distributed around Qinghai Lake and decreasing as we traveled outward, and the high-value area significantly increased. The high-value area was dominated by medium coverage grassland, and with the increase in precipitation, the supply of soil moisture to the vegetation also gradually increased, the photosynthetic rate was enhanced, and carbon sequestration was elevated. The mean values of Habitat Quality (HQ) in five years were 0.63, 0.68, 0.63, 0.68, and 0.77, respectively, showing a fluctuating upward trend, with an increase of 22.2% between 2000 and 2018. The percentage of the high-value area continuously increased, and the percentage of the area within the range of 0.8–1 increased from 69.5 to 80.6%, indicating that the ecological protection of the Qinghai Lake Basin improved during the 19-year period of study.

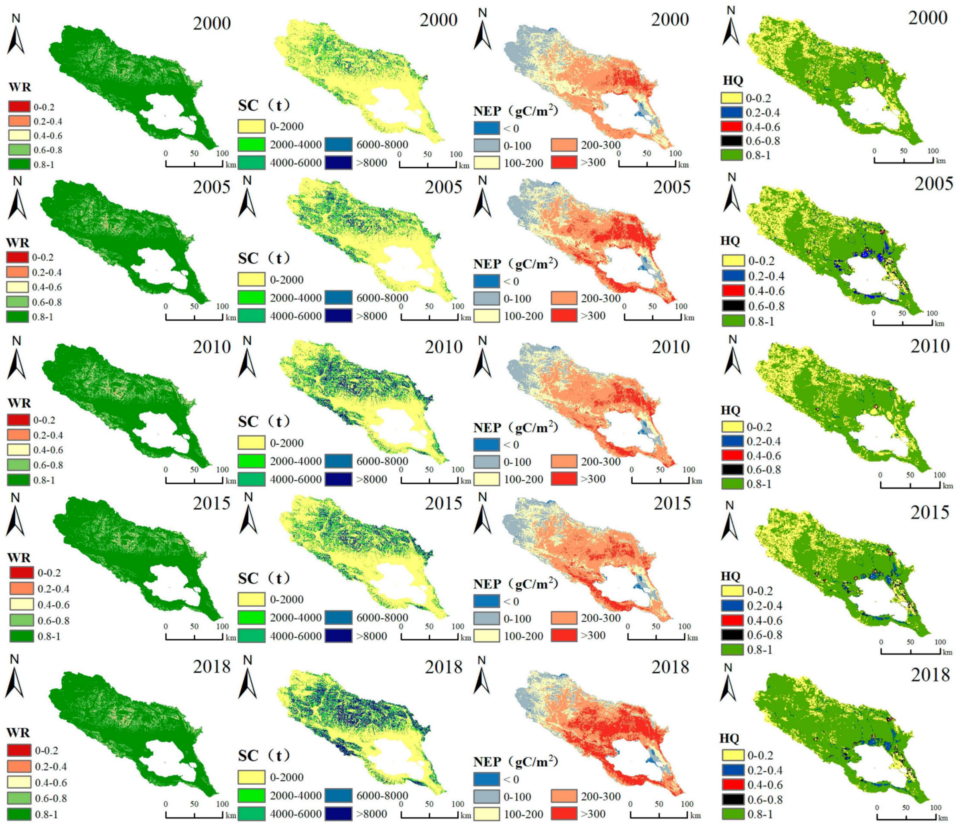

Figure 2. Spatial distribution of ecosystem services in Qinghai Lake Basin between 2000 and 2018 (NEP: carbon storage; HQ: habitat quality; SC: soil conversion; WR: water conservation).

3.2. Spatial Characteristics of Ecosystem Services' Tradeoffs and Synergies

3.2.1. Tradeoff/Synergy Criterion and Tradeoff–Synergy Index in the Watershed

Based on the TSC and the TSI (Figures 3 and 4), the synergy (10.7%) relationship between NEP and HQ was depicted in Qinghai Lake Basin between 2000 and 2018, and the intensities of synergy (0.69) were greater than the intensities of tradeoff (0.57), which is consistent with the spatial distribution change shown in Figure 2. The area of the tradeoff/synergy relationship between NEP and HQ showed an increasing trend in all four periods (2000–2005, 2005–2010, 2010–2015, and 2015–2018). The peaks of the tradeoff/synergy relationships both occurred in the period 2015–2018, with 23.2% being the peak for tradeoff and 32.6% being the peak for synergy. The areas of NEP and SC were mainly in a synergetic relationship (55.5%) and distributed in most areas of the watershed, and the high SC area corresponds to the high NEP area. The synergy between SC and NEP exhibited a high intensity (0.95), with the tradeoff area being 39.7% and the peak intensity of tradeoff being 0.92. The synergy relationship between NEP and SC showed an increasing trend, followed by a decreasing trend, across the four periods, with the maximum value of this relationship occurring in the period 2005–2010 (60.4%). The area that exhibited a synergetic relationship demonstrated a declining trend, followed by an increasing trend, which reached its peak in the period 2015–2018 (75.4%). The areas with synergy relationships showed a significant decreasing trend: the highest value (59.3%) occurred in the period 2000–2005, and the lowest value (24.4%) occurred in the period in 2015–2018. HQ and SC were predominantly influenced by a synergetic relationship (11.8%). However, the tradeoff between HQ and SC (0.70) exhibited a greater intensity than the synergy interaction (0.50). The percentage of the area of the synergy relationship exhibited a pattern of initial increase, followed by decrease and subsequent increase in the four periods (2000–2018). The highest value (38.4%) was observed in the period 2015–2018. The tradeoff relationship exhibited a trend of increase in area, with the highest value being observed in the period 2015–2018 (14.5%), while the lowest value occurred in the period 2000–2005 (0.1%). The relationship between HQ and WR was dominated by tradeoff (12.8%), with a greater intensity of tradeoffs (0.59) than synergies (0.56). The tradeoff/synergy relationship exhibited an increasing trend, reaching its peak in the period 2015–2018, when tradeoffs were 44.5% and synergies were 24.0%. SC and WR were dominated by the tradeoff relationship (61.5%), as shown in Figure 2, in which the areas with high values of WR corresponded to the areas with low values of SC. The tradeoff intensity (0.99) was high, and the largest percentage of the tradeoff relationship area appeared in the period 2005–2010 (74.9%). The synergy relationship accounted for 33.2% and was distributed in the central part of the basin with high synergy intensity (0.99), and the largest area of synergy (58.5%) occurred in the period 2000–2005.

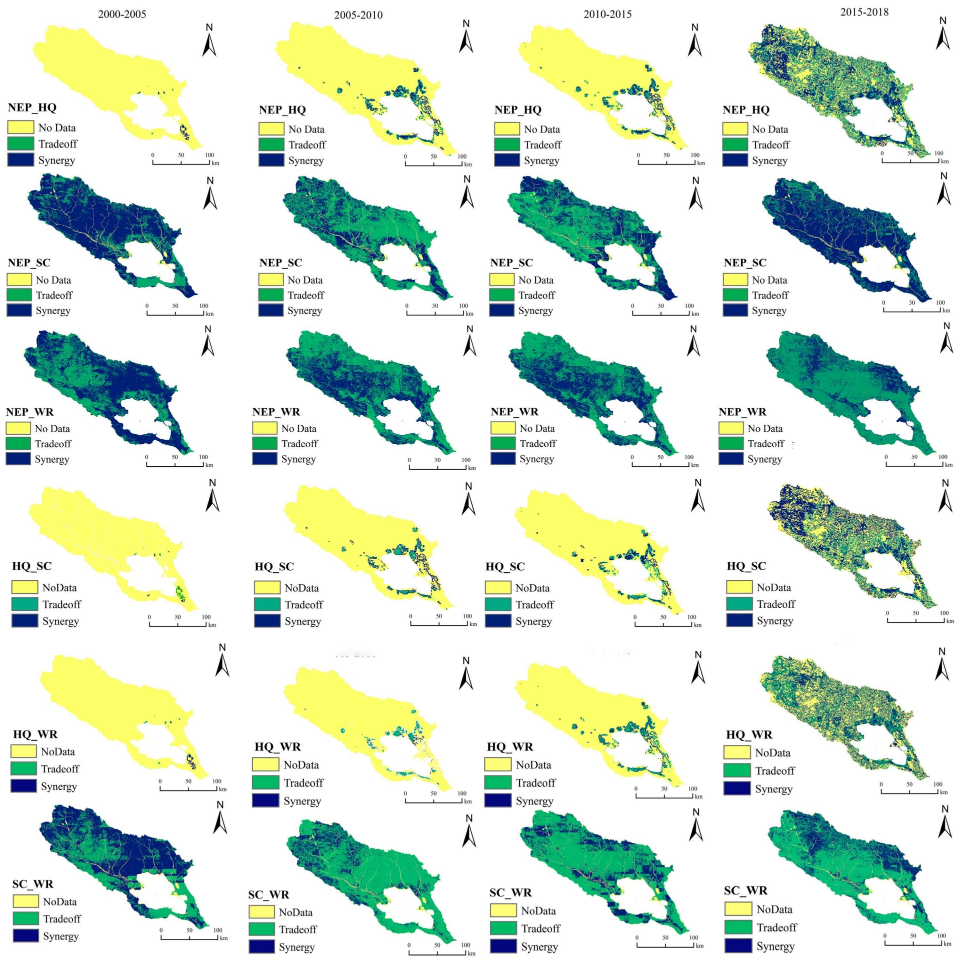

Figure 3. Spatial distribution of tradeoffs and synergies of ecosystem services in the Qinghai Lake Basin (NEP: carbon storage; HQ: habitat quality; SC: soil retention; WR: water conservation capacity).

The most obvious synergy–tradeoff relationships is between NEP and SC, with had a high synergy of 75.4.% in the period 2015–2018, which was distributed in most parts of the basin, and 19.8% tradeoff area, which was mainly found in the northeastern part of the basin. The high-value area of NEP in the watershed reflects the good vegetation cover present in the region, as good vegetation cover provides favorable conditions for precipitation interception and plays a suppressive role in soil erosion caused by precipitation, which explains the high intensity values of the synergy effects of carbon storage and soil retention services [39–41].

Figure 4. Tradeoff–Synergy Index of ecosystem services in Qinghai Lake Basin (NEP: carbon storage; HQ: habitat quality; SC: soil retention; WR: water conservation capacity).

3.2.2. Bivariate Spatial Autocorrelation of Watershed Ecosystem Services

In the bivariate local spatial autocorrelation analysis, high–high and low–low clusters are described as having synergy relationships, and the high–low clusters and low–high clusters are described as having tradeoff relationships. Therefore, we can use the bivariate local spatial autocorrelation analysis to identify the tradeoff/synergy relationships.

Bivariate local spatial autocorrelation analyses of SC, HQ, NEP, and WR functions in Qinghai Lake Basin (Figure 5) reveal that high–high clusters predominate among these four ecosystem service functions, meaning that the four ESs mainly act in synergy. Throughout the entire period, there was a synergy effect between NEP and WR, HQ and SC, NEP and WR, and HQ and WR, while NEP and SC had a tradeoff-based relationship. The relationship between SC and WR was not obvious, as it acted as a tradeoff in the periods 2000–2005 and 2015–2018, while in 2005–2015, it acts as in synergy. The highest values of the tradeoff/synergy areas of ESs were observed between 2000 and 2005. However, a decreasing trend was evident in all of the tradeoff and synergy areas in in the period 2000–2018, except for the NEP and HQ.

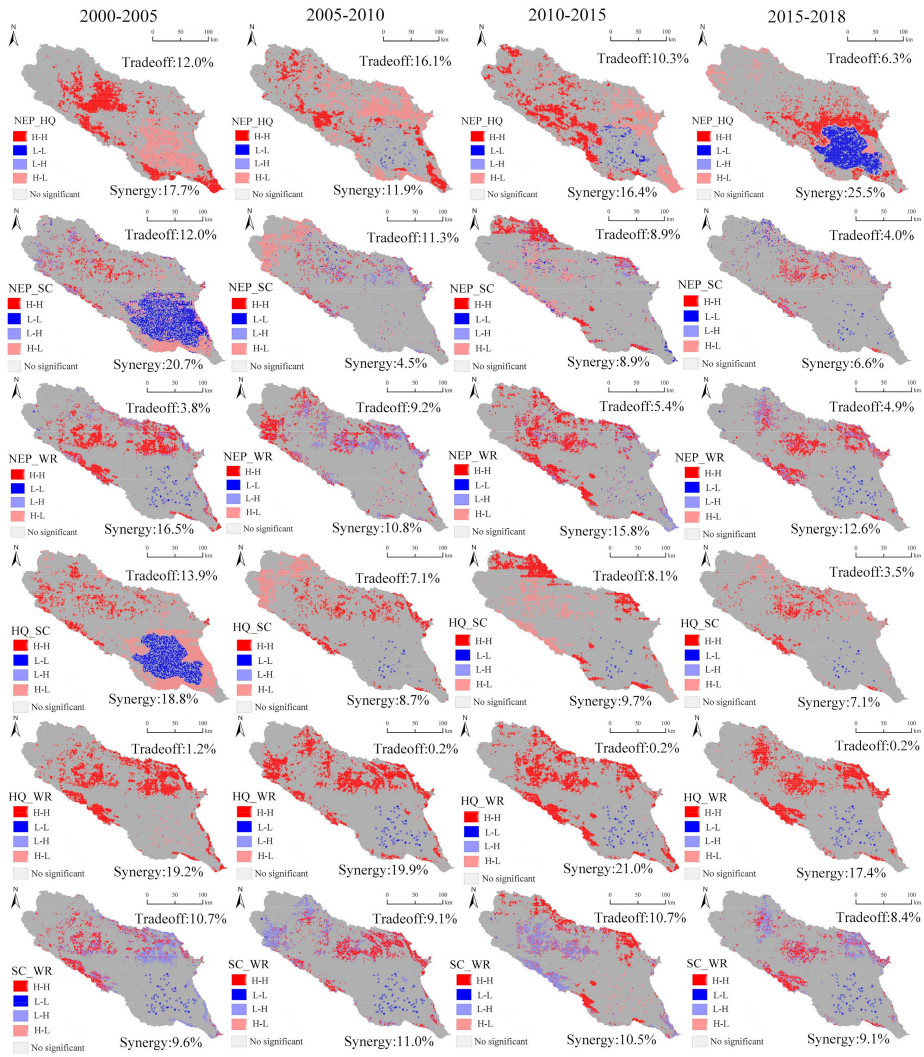

Figure 5. LISA cluster of ecosystem services in Qinghai Lake Basin (NEP: carbon storage; HQ: habitat quality; SC: soil retention; WR: water conservation; H-H: high–high cluster; L-L: low–low cluster; L-H: low–high cluster; H-L: high–low cluster). The numbers indicate trade-offs and synergies as percentages of the overall study area.

High–high clusters of NEP and WR and HQ and WR were mainly distributed in the middle of the watershed, as were clusters of HQ and SC. The high–high clusters of NEP and HQ underwent significant changes, which were mainly distributed in the middle of the basin between 2000 and 2005, before being scattered in the upper area of the basin in the period 2005–2015 and mainly scattered in the northern part of Qinghai Lake in the period 2015–2018. HQ and SC and NEP and SC have similar high–high cluster distribution, as clusters were scattered in the middle and northeastern areas of the watershed. The middle part of the watershed is mostly grassland, which can retain water and contribute to the prevention of soil and water loss. This finding also explains why the high values of the four services are mostly concentrated in the middle part of the watershed.

The location of high–high clusters in the LISA diagram corresponds to the distribution of synergy relationships, as depicted in Figure 3. In Figures 3 and 4, we can see that NEP and SC and HQ and SC showed the same trends in LISA and TSC between 2000 and 2018, as did NEP and SC. The consistency of the two results indicates that the results of TSC are reliable.

4. Discussion

Based on the InVest model, it was found that the soil retention services in the Qinghai Lake watershed showed a fluctuating upward trend, with the high-value areas concentrated in the central part of the Lake and low-value areas distributed around the Lake and in the northwestern part of the watershed, and these findings are consistent with the results of Zhang et al. [42]. The spatial distribution of habitat quality was consistent with the results of previous studies [43]. The NPP was estimated based on the CASA model, and the net ecosystem productivity (NEP) of vegetation was calculated on this basis, being slightly higher than the results estimated by Liu et al. [35] and Zhang et al. [44], probably because of the different input data. Among the six pairs of ESs relationships in the Qinghai Lake Basin, three pairs of ESs—NEP and HQ, NEP and SC, and HQ and SC—showed synergy relationships, and the remaining three pairs of ESs showed tradeoff relationships. The high value of NEP was found in the central part of the watershed, where most of the areas had low-to-medium coverage of grassland and open forest, and the average precipitation rate was high; this area was not the area with the high value of NEP. SC and WR show a strong tradeoff relationship: the low value of SC shown in the Qinghai Lake Basin was the WR's high value, and both WR and SC were sensitive to precipitation [45].

HQ and NEP show the same trend (synergy) in the TSC, as they were both calculated based on the basic land use type. Different types of land have different capacities to store carbon. Similarly, land use type determines the quality of habitat, and better vegetation creates a better environment. LISA reveals a synergy between HQ and WR, while TSC show a unclear result. It can be seen that the high–high clusters of LISA are concentrated in the middle of the basin, in which the main land uses are medium and high grass cover. Better vegetation cover provides better rainfall interception; thus, the water-holding capacity of the area is high, there should be a synergy between the HQ and WR, and the results of LISA between HQ and WR have a stronger correlation. The high-value areas of WR are distributed in the area around Qinghai Lake and the river source area in which SC have low value. The excessive water will cause soil erosion, which explains the tradeoffs between WR and SC. At the same time, the Qinghai Lake and the river source area have low topographic relief and high levels of human activity, which lead to stronger tradeoffs [46]. The spatial role of the tradeoffs between NEP and WR is more obvious, as is that of the SC and WR tradeoffs, mainly because a stable water supply is the basis for maintaining other ecosystem services in the basin [47,48]. In order to reduce the area of the tradeoffs, we need to pay more attention to water management in the Qinghai Lake Basin. The synergy between HQ and SC is due to the fact that the dominant vegetation type in the high-value areas for soil conservation services is grassland, and good vegetation cover improves habitat quality.

Previous studies have shown that climatic factors have a large impact on various ecosystem services; therefore, climate change is a crucial determinant of ecosystem services [49–51]. In recent years, the climate in the Qinghai Lake Basin has shifted toward warmer and more humid conditions, which have created favorable circumstances for vegetation growth (Figure 6). Some scholars have found that climate change is the main factor involved in vegetation coverage change in the watershed [29], while the vegetation is the used to calculate ESs. The increase in precipitation has led to positive changes in watershed ecosystem services, such as heightened carbon storage and improved water conservation capacity. However, excessive precipitation must be closely monitored due to its potential negative impacts. The increase in temperature will accelerate the melting of glaciers and frozen soil, resulting in significant soil erosion. Therefore, it is essential to pay more attention to the climatic changes that occur in the Qinghai Lake Basin.

The method used to evaluate ecosystem services based on the InVest and CASA models has been widely applied both domestically and internationally [51–54]. In this paper, we estimated the soil retention services and habitat quality based on the InVest model, and the NPP was estimated based on the CASA model, allowing us to calculate the NEP and WR. The estimation method of WR was based on the NPP quantitative index assessment method outlined in the ecological protection red line delineation guidelines. The Water Yield module of the InVest model was not selected because it required the use of the same data source for precipitation and potential evapotranspiration data, and the meteorological data used in this study could not be used to estimate potential evapotranspiration data. There were errors and uncertainties in the assessment of ecosystem services, model simulations only analyzed the problem via simulations to simplify it, and the errors came from the model itself and the input data [10]. For example, the NPP quantitative index assessment method adopted in this paper failed to consider the applicability of the method to this study area in a local context, and the base data used for estimation were fused data and site data, which significantly differed. This study only considered water conservation capacity, soil retention services, habitat quality, and carbon storage services, and it failed to fully evaluate the watershed ecosystem services. More services will be considered in future studies, such as sand fixation capacity, food supply, and habitat risk. CMIP has introduced a variety of scenarios set based on future potential climate change, causing ever-more researchers to study the changes in terrestrial ecosystems in each scenario. In the future, six CMIP climate change scenarios will also be considered to predict ecosystem services as a result of climate change.

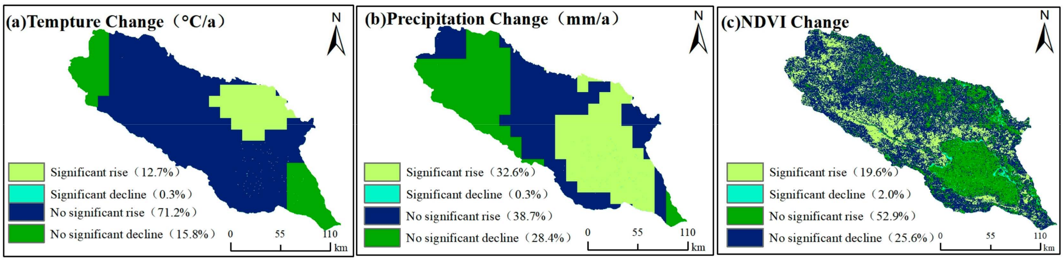

Figure 6. Changes in temperature (**a**), precipitation (**b**), and NDVI (**c**) in Qinghai Lake Basin between 2000 and 2018.

5. Conclusions

This paper quantitatively assessed the characteristics of ecosystem services in the Qinghai Lake Basin in the period 2000–2018 using the InVest model, CASA model, and spatial autocorrelation and redundancy analysis, concluding that:

1. The four ESs—water conservation capacity, soil retention services, habitat quality, and carbon storage—in the Qinghai Lake Basin from 2000 to 2018 showed upward trends. The basin had a high water conservation capacity. The soil retention had an annual growth rate of 130.80 t/a. Carbon storage's average annual growth rate was 1.63 $gC/m^2 \cdot a^{-1}$. Habitat quality showed a fluctuating upward trend represented by an increase of 22.2%.
2. During the period 2000–2018, there was a consistent synergetic relationship between habitat quality and soil retention, as well as habitat quality and carbon storage, while carbon storage services and water conservation capacity and soil retention and water conservation capacity mainly had tradeoff-based relationships. The relationships between carbon storage and soil retention and habitat quality and water conservation are not clear.
3. LISA showed that the relationship between ESs is mainly based on high–high clusters that concentrate in the middle of the basin. The analysis also revealed obvious spatial heterogeneity. LISA validates the TSC results in another way, as carbon storage and soil retention and carbon storage and habitat quality show the same trends in LISA and TSC, as do habitat quality and soil retention. In addition, LISA reveals the result of synergy between HQ and WR, which is more scientific than that of TSC.

Author Contributions: Conceptualization, X.W., L.Z. and L.G.; methodology, X.W., L.Z. and L.G.; software, X.W.; data processing, X.W. and Y.L.; writing, X.W., Y.L. and X.L.; writing—review and editing, Y.L. and X.L. All authors have read and agreed to the published version of the manuscript.

Funding: Funding was provided by the Natural Science Foundation of Qinghai Province (2022-ZJ-711).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: Thanks to the teachers and reviewers and editors for their valuable comments.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

InVest	Integrated Valuation of Ecosystem Services and Tradeoffs
CASA	Carnegie–Ames–Stanford Approach
TSC	Tradeoff–Synergy Criterion
TSI	Tradeoff–Synergy Index
LISA	Local Indicators of Spatial Association
QTP	Qinghai–Tibet Plateau
NEP	Carbon Storage
NPP	Net Primary Productivity
HQ	Habitat Quality
SC	Soil Retention
WR	Water Conservation Capacity
ESs	Ecosystem Services
NDVI	Normalized Difference Vegetation Index
DEM	Digital Elevation Model

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