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Original Article Special Topic on Ecological Assets and Ecosystem Services in the Qinghai-Tibet Plateau

Multi-scale analysis of ecosystem services trade-offs in an ecotone in the Eastern Margin of the Qinghai-Tibetan Plateau

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Abstract: Understanding the trade-offs among ecosystem services (ESs) at multiple scales is a key challenge to effective environmental management. However, the scale effect of ESs trade-offs in the Qinghai-Tibetan Plateau (QTP) has received little attention. This study investigated the scale effects of ESs trade-offs in Bailongjiang Watershed (BLJW), a typical transitional ecotone from the Loess Plateau to the Tibetan Plateau with multiple ESs, intensive human activities and frequent geological disasters in the Eastern Margin of the QTP, China. Four key ESs including food supply (FS), soil conservation (SC), water conservation (WC), and habitat quality (HQ) in BLJW in 1990, 2002, and 2016 were mapped to analyze the scale effects at the watershed, county, and township scales. The results indicated varying scale-related temporal and spatial relationships among FS, SC, WC, and HQ. The trade-offs between FS-SC and FS-WC initially increased and then decreased during 1990-2002 and 2002-2016, respectively, while the trade-offs between SC-WC, SC-HQ, HQ-WC, and HQ-FS first decreased and then increased at the same period. The magnitudes of the trade-offs among the four ESs are in the order of watershed scale > township scale > county scale. Among the major land-use types in BLJW, the trade-offs between WC-FS and between HQ-FS in farmland and grassland were higher than those of other land uses. There is a strong trade-off between SC-HQ in forestland and a weak trade-off between SC-WC in farmland and grassland. The trade-offs between the six ESs pairs varied and were scale-dependent mainly due to spatial heterogeneity in the landscape and in human activities. Understanding the ESs trade-offs at the watershed, county, and township scales provides a scientific basis for the formulation of environmental management strategies at appropriate spatial scales. At the BLJW watershed scale, more attention should be paid on farmland and grassland planning and its management, also, forestland should be enlarged if possible. At the county and township scales, land consolidation and planning should be paid more

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attention to develop ecological agricultural tourism and multi-functional landscapes for strategic spatial planning and integrated watershed management.

Keywords: Ecosystem services; Multi-scale analysis; Spatiotemporal change; Trade-offs; Scale effects

1 Introduction

Ecosystem services (ESs) are the direct or indirect contribution of ecosystems to human welfare, linking natural ecosystems and human societies together (Costanza et al. 1997; Daily 1997; MA 2005). Changes in natural systems, climate change, human activities, and intervention can significantly alter ESs and their interactions (MA 2005; Bennett et al. 2009; Dennis and James 2017; Turkelboom et al. 2018). These interactions are, consequently, represented mainly in the form of neutrality, trade-offs, and synergies, meaning that they can either be unrelated or positively and negatively associated with each other at different scales (Rodríguez et al. 2006; Raudsepp-Hearne et al. 2010; Howe et al. 2014; Lee and Lautenbach 2016; Wu and Li 2019). When there is a trade-off in ESs, the improvement of one ES is at the expense of one or more other services (Rodríguez et al. 2006; Wu 2013). When there is synergy, the provision of one ES enhances the servicing capacity of other ESs (Raudsepp-Hearne et al. 2010; Howe et al. 2014; Wu and Li 2019). ES interactions are not static and any spatial or temporal changes in ESs may be irreversible (Howe et al. 2014; Hou et al. 2017). That is, ESs do not vary independently of each other (Feng et al. 2017). Quantifying ecosystem services in a spatially explicit manner and analyzing trade-offs between them can lead to more effective, efficient, and defensible natural resource management. Evaluating the dynamics of ES interactions is crucial for their management and avoid potentially undesirable trade-offs (Sun et al. 2020). Understanding ESs interactions across temporal scales, therefore, is another key challenge (Mouchet et al. 2014). Furthermore, there are diverse relationships between individual ESs and they can exhibit different patterns across large-scale landscapes (Li et al. 2019). The trade-offs/synergies of relationships between two ESs could threaten the stability and security of a natural ecosystem (MA 2005; Carpenter et al. 2009; Han et al. 2020). Yet, explicit information, guidance, and methods for understanding the interactions among multiple ESs across heterogeneous landscapes remain limited (Qiu and Turner 2013; Liu 2019). Thus, understanding the relationships between ESs plays a vital role in effective ESs management and policymaking (Mach et al. 2015; Wang et al. 2019).

Ecosystem services can interact to form neutral, synergic, and trade-off relationships with each other (Wu and Li 2019). Several sophisticated approaches to the assessment of trade-offs have been developed. These include geostatistical analysis, spatial mapping, and scenario simulation (Dai et al. 2015; Fu and Yu 2016). Statistical methods can identify trade-offs or synergies among ESs, however, they cannot reveal their spatial and temporal differences (Liu et al. 2019). Spatial mapping, scenario simulation, and ESs flow analysis based on geographic information system (GIS) spatial visualization models, including InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) (Sharp et al. 2020), LUCI (Land Utilisation and Capability Indicator) (Trodahl et al. 2017), and SolVES (Social Values for Ecosystem Services) (Sherrouse et al. 2011), can better reveal the spatial pattern and scale effect of the relationships between ESs while taking into account ecological benefits (Zhang et al. 2019a; Sun et al. 2020). Yet, ESs trade-offs analysis and application remains poorly understood due to methodological challenges and lack of case studies in the ecotone with poor natural system. For example, few integrated ecosystem models can be applied to estimate the interactions between ESs (e.g., the ARIES, Artificial Intelligence for Ecosystem Services model) (Villa et al. 2014) compared with the InVEST, LUCI, and SolVES models (Sherrouse et al. 2011; Xu et al. 2018). Also, new cases and comparative studies are still needed to determine the scope and strength of ES relationships, especially for linking ES trade-offs into policy assessment, design, and implementation on multiple scales, especially in the poor ecotone like Qinghai-Tibetan Plateau (Cord et al. 2017; Xu et al. 2018; Liu 2019; Gong et al. 2021).

Scale and scale effects are at the forefront of landscape ecology and geographical sciences (Konarska et al. 2002; Fu and Yu 2016). Quantifying temporal characteristics and spatial scales in trade-offs or synergies of ecosystem services is beneficial to ecosystem management (Dai et al. 2015; Qiao et al. 2019). Some studies on trade-offs among ESs had been carried out from local to global scales (West et al.

2010; Jia et al. 2014; Turner et al. 2014; Zheng et al. 2014; Jopke et al. 2015; Gong et al. 2019a; Bai et al. 2020). However, ESs are generated by ecological processes of different scales and react in complex ways across scales (Scholes et al. 2013; Fu and Yu 2016; Su et al. 2020). The relationship between an ES pair can vary depending on the scale and the socio-ecological system (Hein et al. 2005; Bennett et al. 2009; Yu et al. 2020). Thus, ecosystem service trade-offs are scale-dependent, and different scales reflect different spatial characteristics and laws (Wu 2004; Hou et al. 2017; Li et al. 2019). For example, ES trade-offs have been documented at the regional, county, and pixel scales in the Taihu Lake Basin (Qiao et al. 2019; Bai et al. 2020). Zhang and Wu (2019) found that there were significant differences in ESs trade-offs and synergies at the city scale, county scale, and 1-km grid-scale in Beijing-Tianjin-Ji Region in China. Wu and Lu (2021) found that there are significant spatial scale effects in the stream water quality of the Yongjiang Watershed of Zhejiang in eastern China. Wen et al. (2019) investigated the scale effect of vegetation restoration on soil and water conservation at regional and sub-watershed scales in a semi-arid region in China through spatial modeling and mapping. However, the ES trade-offs obtained at one scale are often inconsistent with those obtained at another (Wu 2004; Su et al. 2020; Wen et al. 2019; Bai et al. 2020) and thus cannot be used directly for ES management and resource conservation. The main reason for the inconsistency are the scale mismatch between ES supply and demand and the changes in natural conditions, ecological processes, and socio-ecological systems at different scales (Rodríguez et al. 2006; Wang and Fu 2013). Additionally, cross-scale interactions of ecological processes generally lead to outcomes that are unpredictable in single-scale scenarios (Su et al. 2020). As a consequence, a narrow understanding of ES trade-offs limits managers in their ability to take the measures required to improve regional ESs (Sun et al. 2016). Therefore, it is necessary to explore ESs trade-offs and synergies from a multiple scales perspective to support local and regional ESs enhancement and management via considering scale effect on interactions between ESs (Kareiva et al. 2011; Grêt-Regamey et al. 2013; Han et al. 2020; Yang et al. 2021).

The Qinghai-Tibetan Plateau (QTP), known as the "Third Pole of the Earth" and the "Asian Water Tower", provides multiple vital ESs such as water, timber, biodiversity, and recreational opportunities, but its ecosystems are endangered by climate change and human pressures (Liu et al. 2017). The QTP is also an important component of the "Ecological Security Pattern of Four Ecological Barriers and Four Belts" (The "Four Ecological Barriers and Four Belts" is the abbreviation of the "Master plan of national major ecological system protection and restoration protection". It is the first comprehensive plan involving ecosystem protection and restoration after the 19th National Congress of the Communist Party of China in 2017, which plays a significant strategic and guiding role in undertaking related tasks. It also represents a successful initiative for jointly organizing major projects related to natural resources across departments, disciplines, and regions) (Guan et al. 2021). Some studies have attempted to quantify the impact of human activities on the QTP ecosystems and their services. For example, Xie et al. (2003) classified the ESs and functions of the QTP into 15 groups, including climate regulation, food production, and water regulation, and calculated their value. Li et al. (2018) presented the impact of ESs value and human activity intensity in the QTP. An evaluation of the grassland ecosystem of the QTP identified various land use functions and their values (Fan et al. 2018). However, previous studies have mostly focused on the calculation of the value of ESs and assessed the supply of a single ES. Besides, due to the diverse landscape and the spatial heterogeneity of the QTP, there is huge variability in ESs. There is little research on the variation of ESs and their trade-offs. Therefore, in this study, the Bailongjiang Watershed (BLJW) in southern Gansu, a typical ecotone in the Eastern Margin of QTP, was selected as a case to study the spatial scale dependence of ESs relationships. Meanwhile, based on the RMSD method, this study constructed a framework for the study of ESs trade-offs relationship. We studied the trade-offs of four ESs (food supply (FS), soil conservation (SC), water conservation (WC), and habitat quality (HQ)) at multiple scales. The specific objective was to optimize the ESs trade-offs to enhance and manage ESs at multiple scales. Spatial modeling and mapping methods were employed to (1) analyze the heterogeneity of ESs at different scales and quantitatively evaluate their trade-off relationships; (2) explore the impact of different land-use types on ES trade-offs; (3) reveal the scale effects of ESs for ESs protection and enhancement.

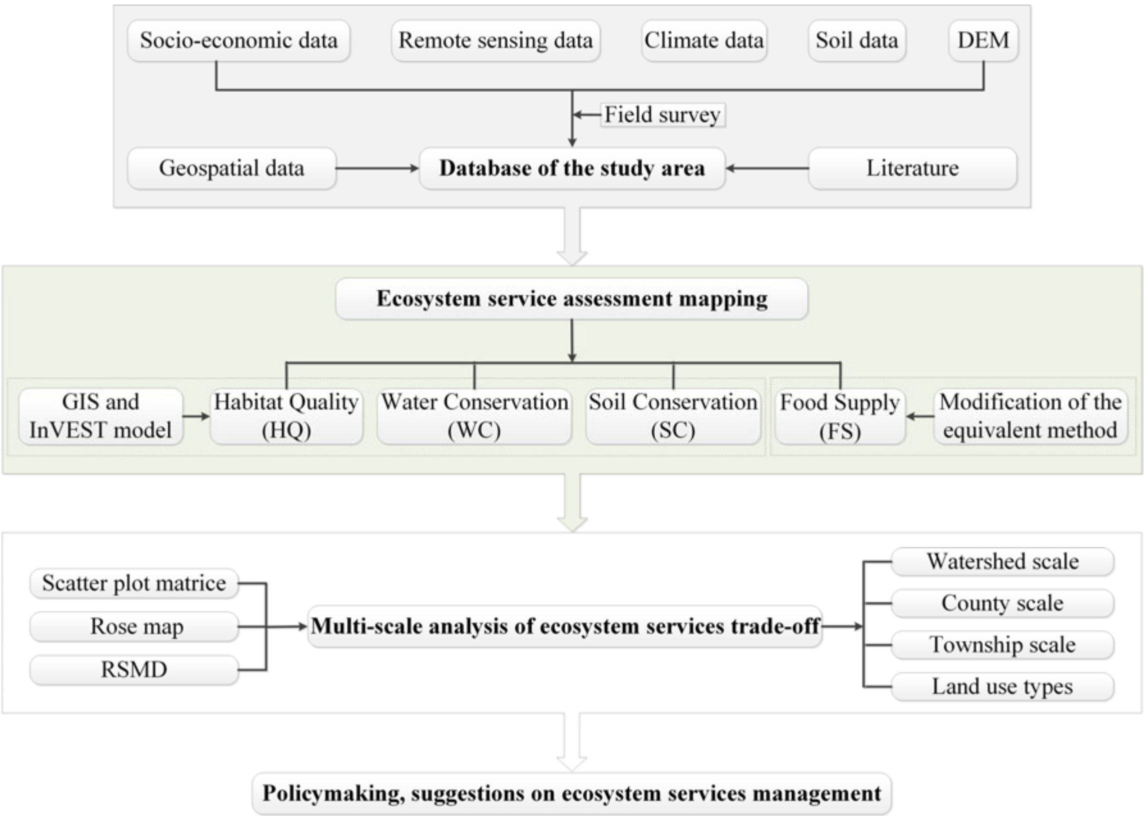

Fig. 1 Research flowchart of ecosystem services trade-offs in the Bailongjiang Watershed. DEM-Digital Elevation Model, GIS-Geographic Information System, InVEST-Integrated Valuation of Ecosystem Services and Tradeoffs, RSMD-Root mean square deviation.

2 Materials and Methods

Fig. 1 shows a flow chart of the methodology used to conduct the study of ESs trade-offs at different scales in a typical ecotone, Bailongjiang Watershed, in the Eastern Margin of the Qinghai-Tibetan Plateau. We first assessed and mapped the main ESs of FS, SC, WC, and HQ of the study area via the InVEST model and a GIS platform. Then we explored the relationships between ESs trade-offs and synergies on watershed, county, township scale, and land-use types. Finally, we proposed some suggestions for ESs management and ecological protection (Fig. 1).

2.1 Study area and data

The Qinghai-Tibetan Plateau (QTP) extends from the Pamir and Hindu Kush Mt. in the west, the Hengduan Mt. in the east, the Kunlun and Qilian Mt. in the north, and the Himalayas Mt. in the south. With an average elevation of over 4000 meters, it is the largest and highest plateau on earth. The Bailongjiang watershed (BLJW) is located in the typical topographical and climatic transitional zone in the eastern edge of QTP (32°36′N-34°24′N, 103°30′E-106°00′E). It includes five counties like Diebu, Tanchang, Zhouqu, Wudu, and Wenxian (Fig. 2). The study area is 1.84×10^4 km^2. The climate belongs to the transitional zone from the subtropical to the northern temperate zone, with annual precipitation of 500~900 mm and annual average temperature ranging 2°C~15°C. The main geomorphic types are mountains, plateau, and valleys, with huge landscape heterogeneity, special geological background, and many kinds of mountainous hazards such as collapse, landslides, and debris flow (Gong et al. 2019b). The rapid development of the economy and acute human-land conflicts has led to increasing pressure on the ecological environment of the entire watershed (Gong et al. 2021). Furthermore, with the implementation of ecological restoration projects such as the Grain for Green Project, Natural Forest Protection Programs, Wildlife and Nature Reserve

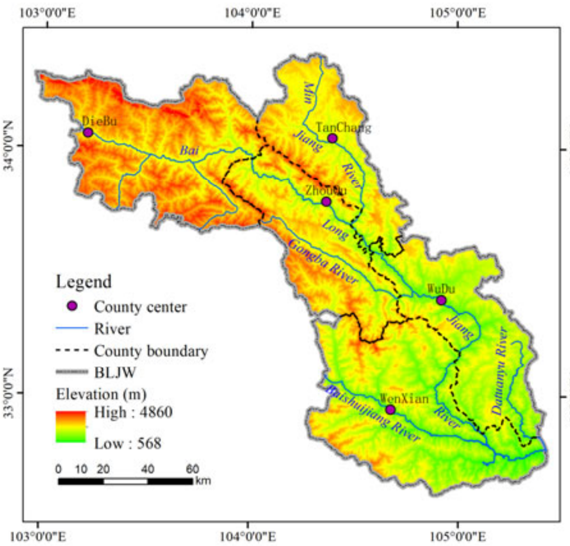

Fig. 2 Location of the Bailongjiang Watershed (BLJW) in the eastern margin of the Qinghai-Tibetan Plateau (QTP).

Construction, the ecological quality of BLJW has been effectively improved gradually (Gong and Xie 2018).

The data used in this study mainly included spatial data and climate data. Land-use maps of 1990, 2002, and 2016 with a spatial resolution of 30 m were interpreted from Landsat TM data provided by the United States Geological Survey (https://www.usgs.gov/). According to the "Chinese Classification Criteria of Current Land Use" (GB/T21010-2017), land-uses were classified into farmland, forestland, grassland, water, constructed areas, and unused land. The overall accuracies in 1990, 2002, and 2016 were 89.02%, 90.71%, and 93.58%, respectively, which is acceptable for land-use change analysis (Gong and Xie 2018). The digital elevation model (DEM) data with a spatial resolution of 30 m of BLJW was obtained from the Geospatial Data Cloud in China (http://www.gscloud.cn/). The 1:1000 000 Chinese soil types spatial distribution data were obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/). Monthly rainfall, total solar radiation, monthly temperature data were obtained from 18 meteorological stations in BLJW and its adjacent counties and the Chinese meteorological dataset (http://data.cma.cn/). Statistical data, including grain production and socio-economic data, were obtained from the statistical yearbooks of the five counties of 1990, 2002, and 2016.

2.2 Methods

2.2.1 Food supply

Food supply (FS) is an important component of the provisioning service for humankind. However, the economic value of FS of regional ecosystems is affected by the local environmental conditions and the degree of social development and changed due to the spatial heterogeneity of local natural conditions when considering regional land use/cover types as the corresponding ecosystem types (Gong et al. 2021). Considering the spatial heterogeneity of natural systems (obtained from Eq. (1)) and social-economic development (obtained from Eqs. (2) and (3)) (Li et al. 2015; Gong et al. 2021), NPP (Net Primary Productivity), the degree of shortage of cultivated land resources, and social willingness to pay (Tao et al. 2005), the value equivalent of each land-use types (LU) were modified. The food supply service was calculated via the model (Xie et al. 2010, Gong et al. 2021):

$$A_i = b_i / B_i \quad (1)$$

$$D_i = c_i / C_i \quad (2)$$

$$L = \frac{1}{1 + e^{(3-1/En)}} \quad (3)$$

$$\mathrm{FS} = \sum \mathrm{VC}_i \times \mathrm{E}_i \times (\varphi_1 \times \mathrm{A}_i + \varphi_2 \times (\mathrm{D}_i + \mathrm{L})) \quad (4)$$

where A_i is the proportion of net primary productivity (NPP) for LU_i (land-use type *i*, hereafter) in BLJW, with b_i and B_i representing the average NPP per unit area of LU_i in BLJW and entire China, respectively. D_i is the proportion of arable land resources of BLJW for year *i*, c_i and C_i are the per capita farmland area (ha/person) in BLJW and in entire China in year *i*, respectively. *L* is the social development index, *e* is the base of a natural logarithm, and *En* is the regional Engel coefficient. VC_i is the coefficient of food production value of LU_i ($RMB{\cdot}hm^{-2}$), E_i is the area of LU_i (hm^2), φ_1 and φ_2 are weights. All the indicators were standardized. The revised method presented here has considered the difference between natural conditions and socio-economic development. Moreover, it also considered the dynamic change via the estimation of the socio-economic development and ecological resource scarcity (Li et al. 2015; Gong and Xie 2018; Gong et al. 2021).

2.2.2 Soil conservation

Soil conservation (SC) is the soil retained by ecosystems within a certain period. The SDR module of the InVEST model regards the sum of soil erosion reduction and retention as soil conservation amount. The model takes into account the role of vegetation in reducing erosion and retaining the sand on the slopes (Su et al. 2020). Soil conservation can be calculated from the following equations (Kareiva et al. 2011; Sharp et al. 2020):

$$\mathrm{SEDRET}_x = \mathrm{PKLS}_x - \mathrm{USLE}_x + \mathrm{SEDR}_x \tag{5}$$

$$\mathrm{PKLS}_x = R_x \cdot K_x \cdot \mathrm{LS}_x \tag{6}$$

$$\mathrm{USLE}_x = R_x \cdot K_x \cdot LS_x \cdot C_x \cdot P_x \tag{7}$$

$$\mathrm{SEDR}_x = \mathrm{SE}_x \sum_{y=1}^{x-1} \mathrm{USLE}_y \prod_{z=y+1}^{x-1} (1-\mathrm{SE}_z) \tag{8}$$

where SEDRET_x, PKLS_x, USLE_x, and SEDR_x are the amount of soil conservation (t), potential soil erosion (t), actual soil erosion (t), sediment retained (t) on pixel x, respectively. USLE_y is the actual soil erosion amount of uphill pixel y; SE_x is the sediment retained rate of pixel x; SE_z is the sediment retained of uphill pixel z; R_x, K_x, LS_x, C_x, and P_x are the rainfall erosivity ($\mathrm{MJ \cdot mm \cdot hm^{-2} \cdot h^{-1} \cdot a^{-1}}$), the soil erodibility ($\mathrm{t \cdot hm^2 \cdot h \cdot hm^{-2} \cdot MJ^{-1} \cdot mm^{-1}}$), a slope length-gradient factor (dimensionless), a crop management factor (dimensionless), a support practice factor (dimensionless) on pixel x, respectively. Here, R_x was calculated by a simple algorithm based on monthly precipitation data. K_x was calculated by the EPIC model (Sharp et al. 2020), and the required data included the specific gravity of soil sand, silt, clay, and organic matter content (%). LS_x was calculated in sections with a turning slope of 25° (Diodato 2010). C_x, P_x, and SE_z of each land-use type were obtained from field observation and/or the value assigned according to the results of similar regions (Gong and Xie 2018; Liu 2019).

2.2.3 Water conservation

Water conservation (WC) refers to the water retained in ecosystems within a certain period. We estimated WC by using the following model, which was revised from the InVEST model (Sharp et al. 2020). Water conservation can be calculated as (Kareiva et al. 2011; Sharp et al. 2020):

$$\mathrm{WC} = \min\left(1, \frac{249}{V}\right) \times \min\left(1, \frac{0.9 \times \mathrm{TI}}{3}\right) \times \min\left(1, \frac{K_{\mathrm{soil}}}{300}\right) \times Y \tag{9}$$

$$\mathrm{TI} = lg\left(\frac{\text{Watershed pixel count}}{\text{Soil depth} \times \text{Percent slope}}\right) \tag{10}$$

$$Y_{x,j} = \left(1 - \frac{\mathrm{AET}_{x,j}}{P_x}\right) \times P_x \tag{11}$$

where V is the velocity coefficient; TI is the topography index; K_{soil} is the saturated hydraulic conductivity of the soil (cm $\mathrm{d^{-1}}$) and calculated by the mass fraction of clay, silt, and coarse sand in the Wosten model, Y is the water yield. Watershed_pixel_count is the pixel count of catchments; Soil_depth is the depth of soil (mm) obtained from the second Soil survey of Gansu Province and field observations; Percent_slope is the slope percentage; $Y_{x,j}$, $\mathrm{AET}_{x,j}$ are the annual water yield (mm) and the actual annual evapotranspiration (mm) for pixel x in landscape j, respectively; P_x is the annual precipitation on pixel x (mm). Here, P_x was obtained via spatial interpolation of monthly precipitation from meteorological stations.

2.2.4 Habitat quality

The InVEST model uses habitat quality as proxies for biodiversity, estimating the extent of habitat and vegetation types across a landscape and their state of degradation (Sharp et al. 2020). The InVEST Habitat Quality model combines information on land use and land cover change (LULC) and threats to biodiversity to produce habitat quality maps (Sharp et al. 2020). Land use/cover maps, threats data, and other related parameters for 1990, 2002, and 2016 were input to run the model. Habitat quality was calculated from Eqs. (12) and (13) (more details can be found in the InVEST User's Guide) (Sharp et al. 2020):

$$Q_{xj} = H_j\left[1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z}\right)\right] \tag{12}$$

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(W_r \Big/ \sum_{r=1}^{R} W_r \right) r_y i_{rxy} \beta_x S_{jr} \tag{13}$$

where Q_{xj} is the habitat quality value of land-use type j; D_{xj} is the total threat level in grid cell x with land-use type j; H_j is a habitat quality score that ranges from 0 to 1, where non-habitat land-use types were given a score of 0 and perfect habitat classes were scored 1, and k is the half-saturation constant (Kareiva et al. 2011; Sharp et al. 2020). W_r is the threat weight that relative destructiveness of a degradation source to all habitats; y was all grid cells; Y_r is the set of grid cells on r raster map, and r_y is raster map r. β_x is the level of accessibility in grid cell x, where 1 indicated complete accessibility. Here, the accessibility of each land cover type was equal. At the same time, the values of relative sensitivity S_{jr} of each habitat type to each ecological threat ranged from 0 to 1, where 1 represented high sensitivity to a threat and 0 represented no sensitivity to a threat (Gong et al. 2019b; Liu 2019).

2.3 Correlation analysis on trade-offs relationship of ecosystem service

In this study, correlation analysis was undertaken to reveal the interaction of ESs. Before analyzing ES interaction, a standardized ES (ES_{std}) was calculated for each ES via the Min-Max normalization method to eliminate the dimensional effects on the different ES, and to obtain the relative benefit value of each ES within a range of 0-1 (Bradford and D'Amato 2012; Liu 2019; Luo et al. 2019). More details on the Min-Max normalization method can be found as follows:

$$\mathrm{ES}_{\mathrm{std}} = \left(\mathrm{ES}_{est} - \mathrm{ES}_{\min}\right) / \left(\mathrm{ES}_{\max} - \mathrm{ES}_{\min}\right) \quad (14)$$

where ES_{est} is the average estimated ES value of each ES; ES_{min} and ES_{max} are the minimum and maximum estimated values. The individual ES_{std} ranges from 0 to 1.

Root mean square deviation (RMSD) was used to quantify the trade-offs and synergies among two or more ESs, as RMSD approximated the average deviation from the mean benefit. RMSD is a simple but effective way to represent the degrees of trade-offs between any two or more ESs, no matter how they are correlated to each other (Lu et al. 2014). More details and illustrations of the trade-offs between two ESs through RMSD can be found as follows (Bradford and D'Amato 2012; Liu 2019; Luo et al. 2019).

$$\mathrm{RMSD} = \sqrt{\frac{1}{n\text{-}1} \times \sum_{\mathrm{i}}^{n} \left(\mathrm{ES}_i - \overline{\mathrm{ES}}\right)^2} \quad (15)$$

where ES_i is the standardized value of ES $_i$, and $\overline{ES}$ is the expected value of ES $_i$. More details can be found from literatures (Bradford and D'Amato 2012; Liu 2019; Luo et al. 2019).

3 Results

3.1 Spatiotemporal pattern of the integrated ecosystem services

In this study, we analyzed four ESs (FS, SC, WC, and HQ) and revealed the change in total relative benefit (TRB), the sum of the standardized individual ES, in BLJW in 1990, 2002, and 2016. The TRB of the BLJW can be divided by ArcGIS into five levels according to the TRB value. Five TRB levels were obtained as: level I (0≤ TRB < 0.5), level II (0.5 ≤ TRB <1), level III (1 ≤ TRB <1.5), level Ⅳ (1.5 ≤ TRB <2), level Ⅴ (2 ≤ TRB <2.8). The spatial distribution of TRB in 1990, 2002, and 2016 was higher in the eastern parts of BLJW than in the western parts, characterized by a spatial distribution of multi-cores (Fig. 3). As shown in Fig. 3 and Table 1, the major level of TRB in the BLJW is level Ⅲ (1≤TRB <1.5), and the area percentages of level Ⅲ in 1990, 2002, and 2016 were 62.84%, 62.61%, and 56.70%. With the change of time, the areas of levels Ⅰ and Ⅳ decreased and then increased. The areas of levels Ⅱ and Ⅲ increased significantly. Meanwhile, the area of the

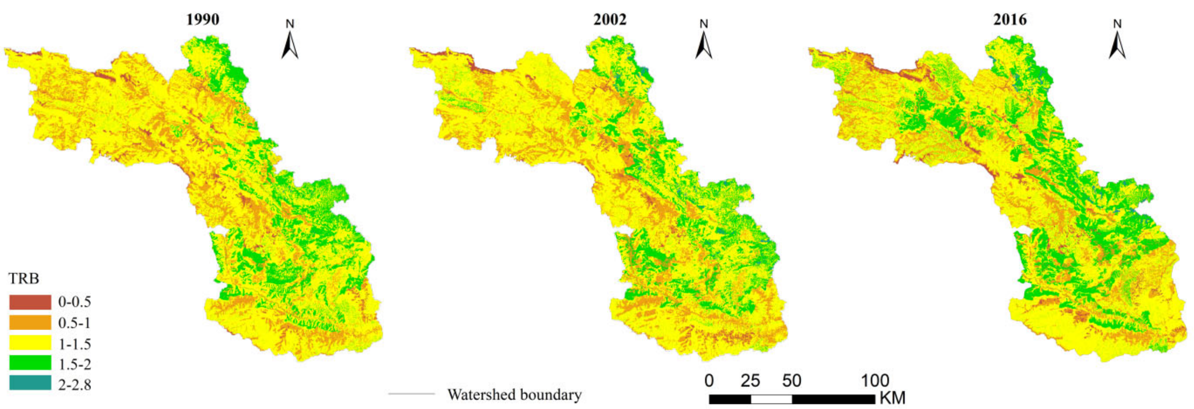

Fig. 3 Spatial and temporal distribution of the total relative benefit (TRB) of ecosystem services in the Bailongjiang Watershed in 1990, 2002, and 2016.

Table 1 Areal proportion and rank of total relative benefits of ecosystem services in the Bailongjiang Watershed in 1990, 2002, and 2016.

Index Rank	Value	Areal proportion of ecosystem services 1990	2002	2016
Ⅰ	0-0.5	2.14%	1.99%	2.97%
Ⅱ	0.5-1	18.72%	18.69%	16.20%
Ⅲ	1-1.5	62.84%	62.61%	56.70%
Ⅳ	1.5-2	16.12%	15.76%	23.29%
Ⅴ	2-2.8	0.18%	0.95%	0.84%

level V initially increased and then decreased (Fig. 3).

3.2 Multi-scale analysis of ESs trade-offs and synergies

3.2.1 Multi-scale analysis of six pairs of ESs trade-offs and synergies

The scatter plot matrices of the absolute value of canonical loadings were applied to visually demonstrate the relationship of ESs with the Origin software. Six pairs of ESs (SC-WC, SC-FS, SC-HQ, HQ-WC, HQ-FS, and FS-WC) passed the significance test ($P < 0.01$). The scatter plot matrices of the six pairs of ESs and their trade-offs (RMSD) in 1990, 2002, and 2016 are shown in Fig. 4 and Fig. 5.

The trade-offs among the six ESs pairs varied greatly in 1990, 2002, and 2016 on the watershed scale (Fig. 4, 5A). The trade-offs of SC-WC was the lowest, and the trade-offs of SC-HQ was the highest. The trade-offs values of the four pairs of ESs, including SC-WC, SC-HQ, HQ-WC, HQ-FS, initially decreased in 2002 and then increased in 2016, while the trade-offs of SC-FS and FS-WC initially increased in 2002 and then decreased in 2016 (Fig. 4, 5A).

At the county scale (Fig. 4), the degree of relative aggregation of each ES pair changed noticeably (Fig. 4). The discrete points of SC, WC, and HQ are mostly distributed on both sides of the 1:1 line (that is, the line of $y=x$). The results show that there is a synergy among SC, WC, and HQ. The discrete points of FS- SC, FS-WC, FS-HQ are mainly distributed vertically along the 1:1 line, indicating that there is a trade-off relationship (Fig. 4). The trade-offs between all ES pairs varied significantly (Fig. 5A). For example, the RMSD values of FS-WC, HQ-FS, SC-FS were higher than those of the other two ESs pairs (Fig. 5A),

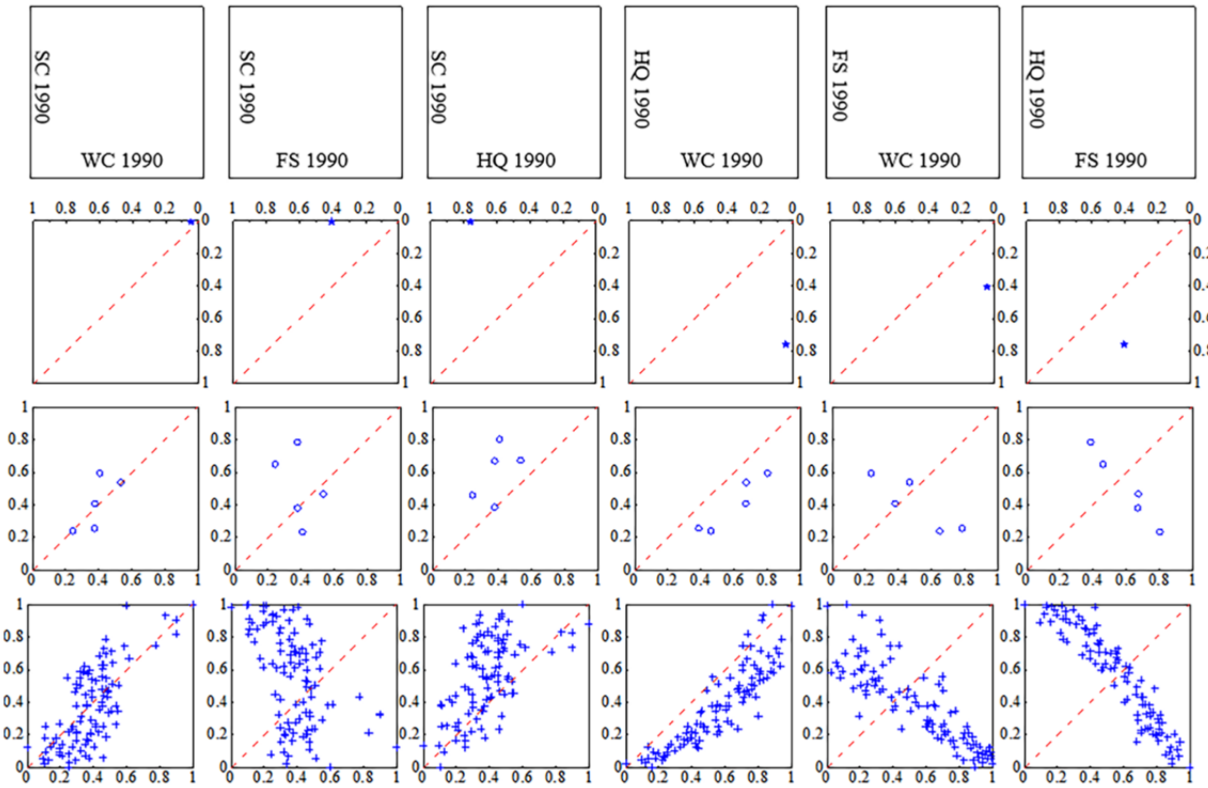

Fig. 4 The scatter plot matrices of six ecosystem services pairs (SC-WC, SC-FS, SC-HQ, HQ-WC, HQ-FS, and FS-WC) trade-offs at watershed, county, and township scale in the Bailongjiang Watershed in 1990, 2002, and 2016. FS-food supply, SC-soil conservation, WC-water conservation, HQ-habitat quality.

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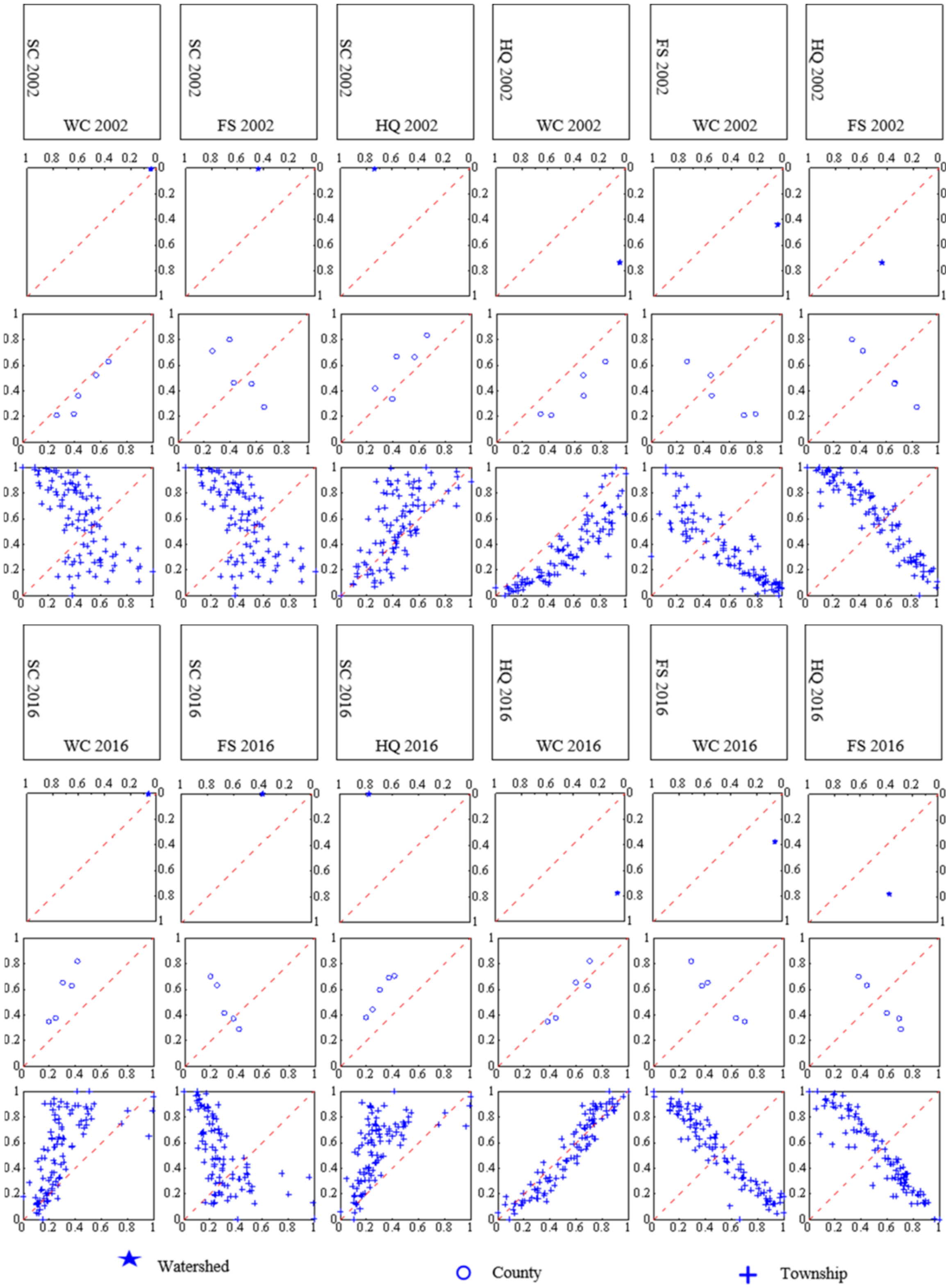

Fig. 4 The scatter plot matrices of six ecosystem services pairs (SC-WC, SC-FS, SC-HQ, HQ-WC, HQ-FS, and FS-WC) trade-offs at watershed, county, and township scale in the Bailongjiang Watershed in 1990, 2002, and 2016. FS-food supply, SC-soil conservation, WC-water conservation, HQ-habitat quality.

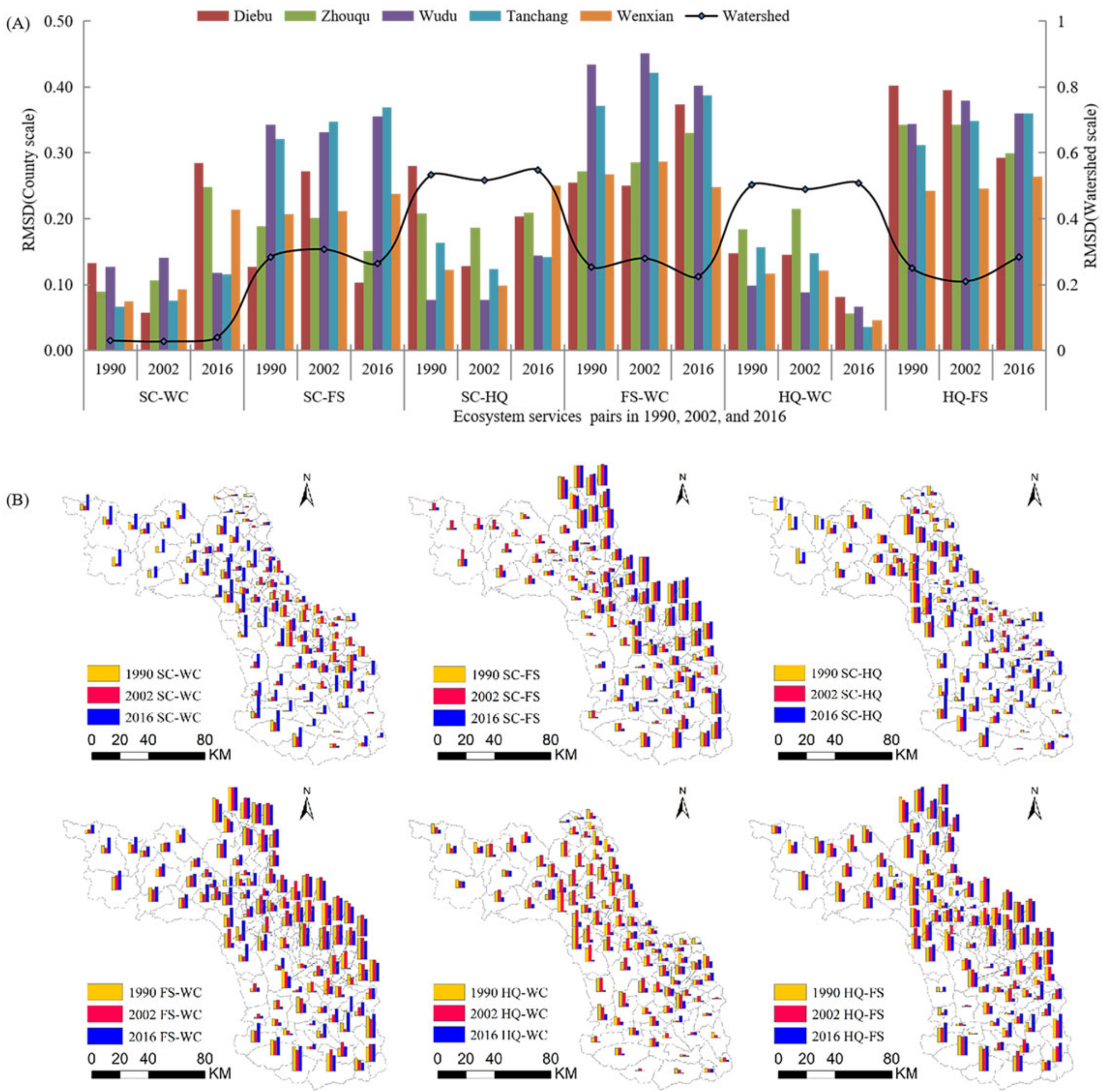

Fig. 5 The change of the root mean squared deviation (RMSD) of the six ecosystem services pairs (SC-WC, SC-FS, SC-HQ, HQ-WC, HQ-FS, and FS-WC) at the watershed (A), county (A), and township scale (B) in the Bailongjiang Watershed in 1990, 2002, and 2016. RMSD-Root mean squared deviation, FS-food supply, SC-soil conservation, WC-water conservation, HQ-habitat quality.

showing that there are apparent trade-offs among these three ESs pairs, especially for FS-WC (Fig. 5A).

At the township scale (Fig. 4, 5B), compared to the county scale, there is an apparent trade-off relationship for each ES pair. The overall trend of the six ESs pairs was very similar to that at the county scale. However, in 2002, the trade-off between WC and SC was stronger than at the county scale. The trade-off values of HQ and WC in 2016 were close to the 1:1 line, indicated that there is a very low trade-off between HQ and WC. The trade-offs values of FS-SC, FS-HQ, SC-HQ in 1990 deviated from the 1:1 line to some extent, compared to the changing trend of 2002. In 2016, the trade-off values were closer to the 1:1 line, which indicated that the trade-off values tend to initially increase and then decrease. There are different changes in the trade-off relationships of all six ESs pairs across townships in the BLJW (Fig. 5B).

3.2.2 Trade-offs analysis of the total relative benefits of multiple ESs

The trade-offs of the total relative benefits (TRB) of the four ESs in different spatial units, including township, county, and watershed were explored by adjusting the scale of analysis (Fig. 6). At the watershed scale, the RMSD of the TRB did not change significantly in 1990, 2002, and 2016. The mean RMSD of the TRB was 0.353 in 2002, 0.347 in 1990, and 0.356 in 2016. On the county scale, the RMSD of three counties, including Zhouqu, Wudu, and Tanchang in BLJW increased from 2002 to 2016. The RMSD of other two counties increased first and then decreased, and then the RMSD of the TRB increased. At the township scale, the RMSD of the TRB gradually increased from 1990 to 2016 (overall mean=0.256, 0.266, and 0.273). To sum up, the trade-off values (RMSD) of TRB of four ESs decreased as Watershed scale > Township scale > County scale (Fig. 6).

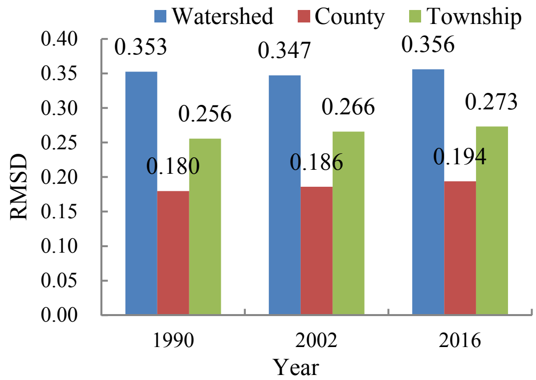

Fig. 6 The change of the root mean squared deviation (RMSD) of total relative benefit (TRB) at the watershed, county, and township scale in the Bailongjiang Watershed in 1990, 2002, and 2016. RMSD-Root mean squared deviation.

3.3 Analysis of ESs trade-offs and synergies in different land types

3.3.1 Trade-offs and synergies of six ESs pairs of the main land-use types

The main land-use types in BLJW—farmland, grassland, and forestland—were selected to show the difference in trade-offs of the six ESs pairs in the BLJW. The trade-off of HQ-FS in farmland and grassland were higher than those of forestland. The trade-off of SC-FS in farmland was the highest among the three land-use types (Fig. 7). And the trade-off of SC-HQ in forestland was the highest among the three land-use types (Fig. 7). Over time, the RMSD of the six ESs pairs changed significantly. As to the farmland, the RMSD of WC-HQ increased, the RMSD of SC-FS, SC-HQ, WC-FS, and HQ-FS initially increased and then decreased. As to the grassland, the RMSD of SC-WC and WC-HQ increased, the RMSD of WC-HQ, SC-FS, and HQ-FS initially decreased and then increased. As to the forestland, the RMSD of SC-WC and WC-FS increased while that of WC-HQ decreased. Also, the RMSD of SC-HQ and HQ-FS initially decreased and then increased, while that of SC-FS changed in the opposite direction (Fig. 7).

3.3.2 Trade-offs and synergies change of the total relative benefits of the main land-use types

The trade-off values of the total relative benefits are mainly concentrated between 0.2-0.3 for different land-use types (Fig. 8). As to the farmland, the RMSD of the total relative benefits increased from 0.237 in 1990 to 0.273 in 2002, then decreased to 0.249 in 2016 (Fig. 8). As to the grassland, the RMSD of the total relative benefits decreased from 0.246 in 1990 to 0.236 in 2002, then increased to 0.292 in 2016. As to the forestland, the RMSD of the total relative benefits decreased from 0.267 in 1990 to 0.262 in 2002, then increased to 0.291 in 2016.

4 Discussion

4.1 Temporal and spatial changes of ESs trade-offs and synergies

Our research determined that the spatial patterns of synergies and trade-offs among ESs in BLJW were highly heterogeneous and varied depending on the ES pairs. There were trade-offs between ESs pairs of FS-SC, FS-WC, and FS-HQ at the watershed, county, and township scale in BLJW. That is, the increase of food supply (especially via area increase of farmland) will result in the decrease of soil conservation, water conservation and habitat, which was mainly due to the land use conflict between farmland and other land use like forestland, pasture and the constructed land. There were synergies existed between ESs pairs of SC-WC, SC-HQ, and HQ-WC at the watershed, county, and township scale in BLJW. This result was consistent with the findings of other studies (Grasso 1998; Seppelt et al. 2011; Xu et al. 2018; Qiao et al. 2019). However, the spatial patterns of trade-offs and synergies among ESs differed across locations (Emmett et al. 2016; Cord et al. 2017; Gong et al. 2019a; Shen et al. 2020), which mainly due to the formation, spatial distribution, and temporal

Fig. 7 The change of six ecosystem services pairs (SC-WC, SC-FS, SC-HQ, HQ-WC, HQ-FS, and FS-WC) trade-offs of the main land-use types in the Bailongjiang Watershed in 1990, 2002, and 2016.

evolution of ESs interactions are influenced by a combination of drivers including climate, vegetation types, land use, and biodiversity (MA 2005; Raudsepp-Hearne et al. 2010; Carreño et al. 2012; Dai et al. 2015; Fu and Yu 2016; Feng et al. 2017; Hou et al. 2017; Liu 2019). Because these drivers can change depending on the temporal and spatial scales, there are varying relationships among ESs at different scales (Van Overwalle 2005; Su et al. 2020; Bai et al. 2020). That is, the interactions of trade-offs or synergies among ESs tend to be complex with high spatial heterogeneity and spatiotemporal scale dependency (Wu 2004; Hou et al. 2017; Su et al. 2020; Bai et al. 2020; Lü et al. 2020; Yang et al. 2021). More works are still needed in the future to explore the underlying mechanisms of trade-offs or synergies between different ESs.

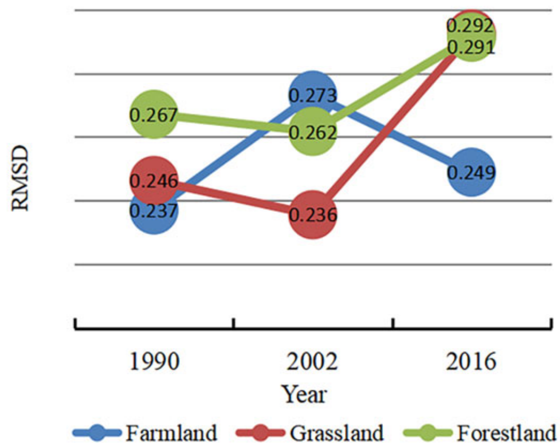

Fig. 8 The change of the root mean squared deviation (RMSD) of the total relative benefit (TRB) of the main land-use types in the Bailongjiang Watershed in 1990, 2002, and 2016. RMSD-Root mean squared deviation.

There are apparent trade-offs relationships among ESs of the main land-use types. The change of trade-offs/synergies during the study period in BLJW were mainly caused by land use transition. The magnitude of the trade-offs between HQ-FS and SC-FS of the main land-use types can be listed as farmland > grassland > forestland, and the values of the trade-offs of SC-WC and WC-FS can be listed as grassland > farmland > forestland. The trade-offs between SC-HQ and between WC-HQ are the largest in forestland compared to that of grassland and farmland. Meanwhile, there was a notable change in land-use structure and patterns during the study period in BLJW as a direct and/or indirect result of human activities, natural disasters, and ecological restoration policies like the Grain for Green Project, the Natural Forest Protection Project, and the New-type Urbanization (Liu 2019). For example, compared with 1990, the areas of farmland, grassland, and unused land of BLJW in 2016 were reduced by 22.58%, 16.53%, and 1.57%, respectively; the areas of forestland, water and constructed land increased by 23.97%, 25.21%, and 109.83%, respectively (Liu 2019). Consequently, this resulted in ESs changes and their trade-offs. These findings are consistent with the research of Bennett et al. (2009), which found that trade-offs are partly caused by land-use change. Meanwhile, land-use changes are linked to changing indicators of ecosystem services through the application of ecological production functions (Yee et al. 2021). Also, Gong et al. (2019a) illustrated that different tradeoffs/synergies relationships existed for different land-use scenarios. Wu et al. (2017) found that the trade-offs among grassland ecosystem services in the high mountainous areas of the QTP changed depending on the management mode and could even be converted into synergy. Therefore, land use planning and optimization can be a useful way to enhance and manage ES via trade-offs (Bennett et al. 2009; Xu et al. 2018; Gong et al. 2019a; Yee et al. 2021). However, more field work and investigation should be carried out to reveal the interaction between ESs and land use, also their response for more reasonable land use planning and management.

4.2 Scale effects of ESs trade-offs and synergies

Previous studies had also confirmed that the relationship between ES may change with spatial scales in Chinese Loess Plateau (Hou et al. 2017; Su et al. 2020; Lü et al. 2020; Yang et al. 2021), in an agricultural watershed in USA (Qiu and Turner 2013), etc. However, there are a few studies conducted in the QTP. It is not appropriate simply to apply the existing knowledge of Chinese Loess Plateau to the QTP as the whole landscape is very unlikely due to the background of environment, land use/land cover, and human activities. Besides, there is a huge demand in ecological construction and environmental management in the QTP via ESs change and their relationship. Therefore, the BLJW was selected to reveal the scale effects characteristics of ESs on the whole watershed, county, and township scale, to provide more accurate information on ES management for decision-makers at different scales for the Eastern Margin of QTP. We found the scale effects on trade-offs among ESs in 1990, 2002, and 2016 in BLJW. There is almost no trade-off between SC-WC at the watershed scale, but there are apparent differences in trade-offs relationships of SC-WC at the county scale. The trade-off values of each county are evenly distributed around the 1:1 line in 1990, while there are low trade-offs in 2002 that benefit SC, and higher trade-offs in 2016 that benefit WC. The distribution of SC-WC at the township scale is similar to that at the county level, which showed there are both high trade-offs and benefits for SC and WC. That is, changing the scale may enhance, reverse, or diminish the relationships among ESs (Sun et al. 2018; Su et al. 2020). Moreover, ESs are associated with varying spatial scales related to their functioning and human welfare (Castellazzi et al. 2010). Thus it is important to fully understand the relationship between ESs indicators across multiple spatiotemporal scales (Mitchell et al. 2015; Bai et al. 2020).

The magnitude of the trade-offs of the total relative benefits across different scales are in the order of Watershed scale > Township scale > County scale. These showed that the trade-offs on at the watershed scale cannot represent those at the county and the township scales. Other scholars have also found a strong spatial scale-dependence in the relationships among ESs in western and northern China (Sun et al. 2017; Wang et al. 2019; Dai et al. 2020; Yang et al. 2021). In other words, the trade-offs between same pair of ESs at different scales are quite different, one possible reason is the influence of scale (Pan et al. 2020; Yang et al. 2021). This means that decision-makers working at different scales need to adopt a multi-scale approach when manage ecosystems, based on the interrelationship between ESs (Yang et al. 2021). However, some studies also found that the relationship between ES was not significantly influenced by scale or the land system except for some ES pairs (Lee and Lautenbach 2016). More attention should be paid to the ESs relationships and their scale effects in the future.

Scale impacts the trade-offs among ESs. This is similar to the results of Su et al. (2020) and Bai et al. (2020). The relationship between a pair of ESs can differ across scales and socio-ecological systems (Hein et al. 2005; Bennett et al. 2009; Fu and Yu 2016; Su et al. 2020; Wen et al. 2019; Bai et al. 2020; Yu et al. 2020). At the same time, it also demonstrates the value of examining different scales to analyze the relationships between ESs, illustrating that multilevel analysis is a means of combining the advantages of both fine scale and coarse scale modeling without losing detail (Cui et al. 2019; Yang et al. 2021). Thus, it is very important to choose the appropriate scale study and apply ES trade-offs. A too large scale may miss some important details, a too small scale may jeopardize the robustness of the research results. We found that the township unit is the appropriate spatial scale for ESs relationship analysis and their management, especially for the transitional area in the Eastern Margin of QTP with diverse fragile landscapes. These results will help us optimize ESs management for both humans and ecosystems.

4.3 Implication for ESs management via the trade-offs and synergies on different scales

The Chinese government promoted several national policies on territorial space planning and integrated watershed management for ecological restoration and environmental governance, especially in the last two decades (Zhang et al. 2019b; Sun et al. 2020; Wu and Lu 2021). These national policies aimed at achieving clean, multifunctional, and sustainable watersheds via the Three Red Lines of "permanent basic cropland protection, urban development boundary, and ecological conservation" for the win-win of "ecological restoration, ecological management, and ecological protection" (Sang and Jan 2016; Sun et al. 2020). Knowledge of the spatial characteristics and changes of ESs could lead to more informed ecosystem management and landscape planning (MA 2005; Li et al. 2019). However, there is still a need for research on ESs science and its application to enhance ESs and promote the integrated management of watersheds (Gong and Xie 2018; Sun et al. 2020; Wu and Lu 2021).

We found that ES trade-offs are scale-dependent, and different scales reflect different spatial characteristics and laws. Also, the relationships vary for different types of ESs and can exhibit different spatial patterns across scales (Fernandez-Campo et al. 2017; Bai et al. 2020). At the BLJW watershed scale, from the perspective of "Three Red Lines of permanent basic cropland protection, urban development boundary, and ecological conservation", more attention should be paid on the planning and manage of farmland and grassland due to the high trade-offs between water conservation, biodiversity, and food production, especially for the lower slope and valley areas. Also, forestland should be enlarged as possible to promote ES like soil and water conservation, biodiversity, aesthetics, etc.. However, there is still a need to determine comprehensive policies basin protection to construct multi-functional land uses and guarantying the ecological security of the watershed in southern Gansu. At the county and/or township scales, scientific planning of land use, environmental protection engineering, urban greening, ecological restoration and management should be paid more attention to improve the living environment. Additionally, land consolidation and planning aiming at the development of ecological agricultural tourism and multi-functional landscapes should focus more on strategic spatial planning and integrated watershed management. More important, such focus would strengthen nature-related aspects with full consideration of future climate, topography, and watershed size. The social and economic development needs should also be carefully considered in the policy of ecological restoration eco-civilization construction to reduce the risk of potential natural disasters and build a watershed community with a shared future (Gong and Xie 2018). However, regional ecological restoration programs and human activities can cause marked unintended consequences with trade-offs across space and time that have undergone little empirical examination (Li et al. 2021). Thus, more studies are still needed to show the time lags and spatial trade-offs caused by regional ecological restoration plans and human activities and provide critical lessons for large-scale restoration programs and human activities.

4.4 Limitation and outlooks

This study illustrated the effects of three different scales (watershed, county, and township scales) on ESs. This study extended the understanding of interactions between ESs depend on spatial scale in the QTP, and the results also demonstrate that decision-makers must be aware of scale effect on the relationships between ESs when managing them. Such awareness may help minimize the uncertainty associated with decision-making which affects trade-offs and synergies (Yang et al. 2021). However, the study inevitably has some limitations in revealing the impacts of different scales on the full range of ESs and their relationship in BLJW due to poor data availability. The study also has limitations in analyzing the complex interrelations between ESs and land-use types. The InVEST model, which has been widely used around the world and was in this study applied for ESs assessment, may also lead to some errors in identifying the ESs relationships due to data limitations, accuracy, spatial variability, and other factors (Gong and Xie 2018; Sharp et al. 2020). Finally, we only determined the spatiotemporal change of ESs and their trade-offs/synergies at the administrative division scale due to its convenience for the formulation and implementation of ecological management. Due to the ES trade-offs are scale-dependent, and ESs may interact in complex ways (Rodríguez et al. 2006; Bennett et al. 2009; Su et al. 2020), more efforts should focus on the scale effects of trade-offs/synergies and their mechanisms in the future, including ESs supply and demand, and their application to decision-making and ESs management (Cord et al. 2017; Bai et al. 2020).

5 Conclusion

The total relative benefit (TRB) of food supply (FS), soil conservation (SC), water conservation (WC), and habitat quality (HQ) experienced significant spatial patterns across the BLJW and were high in eastern BLJW in 1990 and 2016, the TRB improved in the watershed, especially in Tanchang, Wudu, and Diebu during the study period. There are different trade-offs/synergies among the six ESs pairs at the watershed, county, and township scale. There ES trade-offs are scale-dependent, and the magnitude of the trade-offs are experienced as Watershed scale > Township scale > County scale. It is worth mentioning that the township unit is the most appropriate spatial scale to analyze and manage ESs in BLJW. There are apparent trade-offs on WC-FS and HQ-FS between farmland and grassland, also a strong trade-off of SC-HQ in forestland in BLJW, means an apparent trade-off among the main land uses including forestland, farmland and grassland.

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