Ecological Economics, Volume 197, July 2022, Article number 107438
DOI:10.1016/j.ecolecon.2022.107438

# Exploring social-ecological impacts on trade-offs and synergies among ecosystem services

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**Abstract:** An in-depth understanding of the complex patterns of ecosystem services (ESs) interactions (i.e., synergies or trade-offs) based on social-ecological conditions is an important prerequisite for achieving sustainable and multifunctional landscapes. This study aimed to explore how ESs interactions are influenced by social-ecological factors. Taking the Sutlej-Beas River Basin as a case study area, where the linkages between ESs interactions and social-ecological processes are poorly understood, ESs interactions were identified through principal component analysis and correlated with a range of social-ecological factors, which were explored spatially based on ES bundles. The results revealed two dominant types of ESs interactions, namely multifunctionality-related synergies and grain production-related trade-offs. Population, nighttime light, precipitation, temperature, and soil clay content were all positively correlated with the two ESs interactions. Contrarily, elevation and soil sand content were negatively correlated with the two ESs interactions. Four main ES bundles were identified, which spatially describe the presence of ESs synergies and/or trade-offs in relation to social-ecological factors. This study provides a feasible way to explore the spatial differentiation and influencing factors impacting the interactions between ESs, which can provide a basis for an integrated watershed-based management of ESs.

**Keyword:** Ecosystem service trade-offs and synergies, ecosystem service bundles, social-ecological impacts

## 1. Introduction

Ecosystem services (ESs) are broadly defined as the benefits obtained directly or indirectly by humans from ecosystems (MA, 2005), which are the important linkages between the earth's ecosystem and human society (Costanza et al., 1997). Since ESs result from the complex interactions between the ecosystems and humans within the social-ecological system (Perrings et al., 2011; Torralba et al., 2018), the relationships between ES are complicated as well. An increase in one ES may lead to a decrease in another ES due to the trade-off relationship between the two ESs, or an increase in one ES may lead to the corresponding enhancement of another ES due to the synergistic relationship between them (Bennett et al., 2009; Raudsepp-Hearne et al., 2010; Howe et al., 2014). Due to the complexity of ESs interactions, in-depth understanding on the interactions between ESs is needed to reduce unintended trade-offs among multiple ESs and enhance synergies to realize multifunctional landscapes (Costanza et al., 2017; Gissi and Garramone, 2018; Shen et al., 2020). Since the benefits ESs provide to human beings are the basis of socio-economic development, ESs are important in connecting natural ecosystem and the socio-economic system (Fairbrass et al., 2020). At the same time, the supply level of ESs is influenced by a series of socio-economic and ecological factors, resulting in the spatial and temporal differentiation of both ESs and their interactions (Luo et al., 2019). At present, research on ESs has increasingly explored the factors influencing the interaction between ESs in social-ecological systems, to help understand and optimize the objective trade-off relationships, which can sustainably improve human well-being (Torralba et al., 2018; Qiu et al., 2020).

The interdependence of ecosystem functions determines the close relationships between ESs. Based on ES assessment, the analysis of the interaction between ESs can provide key information for the management of ESs (Raudsepp-Hearne et al., 2010; Cord et al., 2017). In recent years, the number of studies on the interactions among ESs has been increasing, mainly including quantitative identification, mechanism analysis and policy response of ES trade-offs and synergies (Dade et al., 2018; Saidi and Spray, 2018; Peng et al., 2020). Previous studies have shown that there is obvious spatial heterogeneity between ES trade-offs and synergies (Shen et al., 2020; Qiu et al., 2020). Spatial heterogeneity in socio-economic and ecological conditions determines the pattern of multiple ESs and thus leads to the spatial differences in ES trade-offs and synergies (Bennett et al., 2009; Potschin et al., 2011; Torralba et al., 2018). Understanding how ESs interact with each other in complex and changing socio-economic and ecological conditions has become one main hurdle to achieve accurate location-based management of multiple ESs (Lee et al., 2016; Rova et al., 2019; McEntee et al., 2020).

Recent research has also highlighted the need to consider ES interactions over space to better understand trade-offs and synergies in a landscape (Qiu et al., 2020; Shen et al., 2020). Therefore, ES bundle approach is commonly used to identify clusters of ESs over space and to assess their association (Raudsepp-Hearne et al., 2010).

Previous studies have shown that different socio-economic and ecological conditions are the controlling factors of the spatial clustering of multiple ESs (Chen et al., 2020; Saidi and Spray, 2018; Schirpke et al., 2019). However, most studies have analyzed the spatial clustering of multiple ESs and their relationship in ES bundles from the perspective of the landscape, and there is still a need for further exploration on how ES bundles are defined by different types of ES interactions as well as how social-ecological factors impact ES interactions within these bundles (Renard et al., 2015; Saidi and Spray, 2018). Accumulated knowledge has demonstrated that an integrated social-ecological approach that links ecosystem services bundles and social-ecological properties is essential (Qiu et al., 2020). Further exploration of the controlling factors underlying the co-occurring ESs and their interactions within different bundles is important to understand the spatial distribution and composition of ES bundles, as well as to coordinate the regional management of ESs.

The Sutlej-Beas River basin was selected for this study because of its importance to food, energy, and biodiversity in the region, and the remarkable variety in environmental and social factors that exists in this Himalayan region (Nepal and Shrestha, 2015; Rasul and Sharma, 2016; Sharma et al., 2020). This study aimed to determine how interactions between ES are controlled by social-ecological factors in the Himalayan region. In details, the main research objectives are: (i) to quantify a set of selected ESs, i.e., grain production, water yield, water purification, soil retention, carbon storage, air quality regulation, and habitat maintenance; (ii) to identify different types of ES interactions and their correlation with a range of social-ecological factors; and (iii) to spatially explore these relationships based on ES bundles.

## 2. Materials and Methods

### 2.1. Study area and data sources

The study area is the Sutlej and the Beas River basins (30°19'N-32°56'N, 74°57'E-82°27'E). The terrain is high in the east and low in the west, with the highest altitude of over 6,800 meters and the lowest altitude of only 173 meters (Fig. 1). It spans the tropical monsoon climate zone and the plateau mountain climate zone (Momblanch et al., 2019). The elevation change of Beas-Sutlej River basin leads to substantial variations in social-ecological factors such as climate, soil, and human activities from upstream to downstream of the study area. At high altitude in the upper reaches of the study area, alpine grassland is the main landscape type. At midstream, the steep terrain is covered predominantly by forest. At low elevation, the flat plains are home to intensively managed and irrigated agriculture, in a region known as the "the breadbasket of India" (Momblanch et al., 2019). Human settlements are found throughout the watershed, with small villages and towns found in the river valleys in the mid and high elevations and larger cities in the low elevation (Rasul and Sharma, 2016).

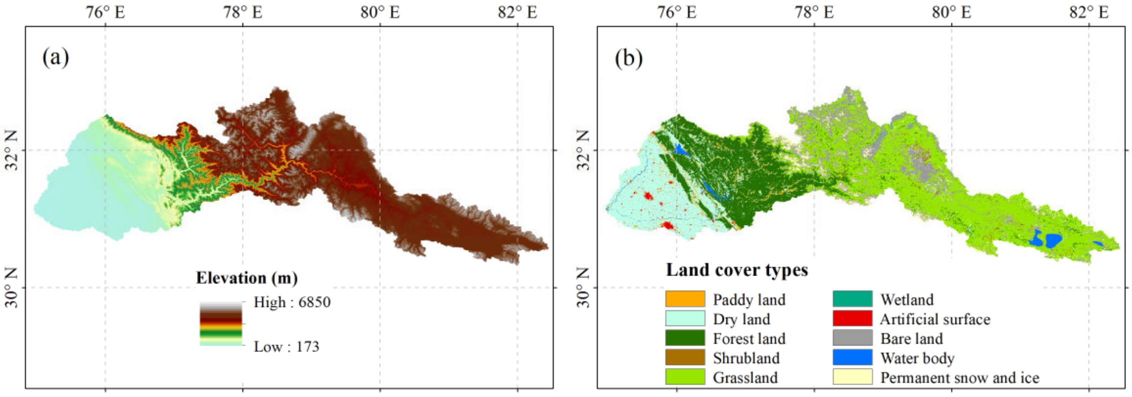

**Fig. 1.** Spatial patterns of elevation (a) and land cover types (b) of the study area.

Four types of spatial and statistical data were used in this study. The first data type includes land cover data and elevation data. Land cover data for 2015 was obtained from the European Space Agency (https://www.esa-landcover-cci.org/). Digital elevation model (DEM) data was supplied by the United States Geological Survey (https://www.usgs.gov/). The second data type is remote sensing data. In details, normalized difference vegetation index (NDVI) data and leaf area index (LAI) data for 2015 were obtained from the National Aeronautics and Space Administration (http://modis.gsfc.nasa.gov). Soil texture data was obtained from the International Soil Reference and Information Centre (https://www.isric.org/). Nighttime light intensity data for 2015 was obtained from the National Oceanic and Atmospheric Administration's Earth Observation Group (https:// www.ngdc.noaa.gov/eog/viirs.html). Population density data for 2015 was derived from the LandScan Global Population Distribution Dataset (https://www.satpalda.com/product/landscan/). The third data type is meteorological data of temperature, precipitation and terrestrial evapotranspiration for 2015. Temperature and precipitation data were supplied by the Climatic Research Unit (http://www.cru.uea.ac.uk/about-cru), and terrestrial evapotranspiration was supplied by the National Aeronautics and Space Administration (https://ladsweb.modaps.eosdis.nasa.gov/). Finally, statistical data for 2015 was obtained from the Statistical Abstract of Economics and Statistics of the Indian states of Himachal Pradesh and Punjab, and the yearbook of the Tibet Autonomous Region, China.

### 2.2. Quantifying ecosystem services

According to the Classification of ESs (CICES) (https://cices.eu/), seven ESs, which play a critical role in social-ecological systems for the study area, were selected and evaluated: grain production, water yield, water purification, soil retention, carbon storage, air quality regulation, and habitat maintenance (Willot et al., 2019; Peng et al., 2018a). The ESs were first quantified at the sub-watershed level, which is regarded as a hydrologically complete unit (Yang et al., 2020), and the sub-watershed is also the smallest geographical unit for which adequate data was available. Because the evaluation indices of different ESs have different dimensions and orders of magnitude (Table 1), the original values of ES index were standardized. Min-max normalization, also known as deviation normalization, was used to normalize the raw data to 0-1 scale.

**Table 1**. Biophysical indicators and units of ecosystem services.

| Ecosystem services | Biophysical indicators | Units |
|---|---|---|
| Grain production | Annual crop yield | $t \cdot ha^{-1}$ |
| Water yield | Annual water production | mm |
| Water purification | Annual nitrogen and phosphorus export | $kg \cdot ha^{-1}$ |
| Soil retention | Difference between potential and actual soil erosion | $mg \cdot ha^{-1}$ |
| Carbon storage | Amount of carbon stored | $t \cdot ha^{-1}$ |
| Air quality regulation | Leaf area index (LAI) | $m^2/m^2$ |
| Habitat maintenance | Level of habitat quality | / |

(i) Grain production

Grain production is directly related to human well-being. In this study, grain production was quantified by combining remotely-sensed data on land cover and agricultural statistical data. The maximum value of NDVI, representing the best condition of crop growth within a given period of time, was used to reconstruct the NDVI time series firstly. Then, the crop NDVI and the yearly statistical data has been used to calculate the grain production of farmland grid. Finally, the grain production of each river basin was summed to obtain grain production yield at the watershed level (Zhao et al., 2018). This approach has been used in previous studies, which have shown that there is a significant linear relationship between grain production and NDVI (Kuri et al., 2014; Peng et al., 2019).

(ii) Water yield

Water yield is an important freshwater related ES and is essential to the survival of human and wildlife. The water yield module of InVEST model was used to estimate the water yield, which is based on the principle of basic water balance that considers three components: surface runoff, soil moisture, and water holding capacity of litter and canopy interception. The Budyko curve and average annual rainfall were used to calculate this service as following (Zhang et al., 2001):

$$Y_{xj} = \left(1 - AET_{xj}/P_x\right) \times P_x \qquad (1)$$

Where $Y_{xj}$ is the water yield in grid $x$, $AET_{xj}$ is the annual evapotranspiration for land cover type $j$ in grid $x$, $P_x$ is the annual rainfall of grid $x$.

(iii) Water purification

Water purification can reduce regional water pollution. In this study, the water purification module of the InVEST model was used to evaluate the interception effects of vegetation and soil on nitrogen and phosphorus. The model uses the capacity of vegetation and soil to remove nutrient pollutants in runoff to estimate their contribution to water purification (Liu et al., 2019).

(iv) Soil retention

Soil loss can destroy the original soil structure, leading to soil degradation and productivity reduction, as well as further adverse effects on social and ecological systems. Soil retention is one of the important ESs in the study area. Using the Revised Universal Soil Loss Equation (RUSLE), soil retention was calculated using the following formula (Okou et al., 2016):

$$A = R \times K \times LS \times (1 - C \times P) \tag{2}$$

Where *A* is the soil retention; *R* is the rainfall-runoff erosivity factor; *K* is the soil erodibility factor; *LS* is the slope length and steepness factor; *C* is the vegetation coverage and management factor; and *P* is the soil retention measures factor.

(v) Carbon storage

Carbon storage is essential for climate regulation (Peng et al., 2019). The carbon storage module of the InVEST model was used to calculate the carbon storage in the study area. This module calculates the aboveground biomass, root biomass, soil organic carbon and humus carbon density of each land cover type. The formula is as follows:

$$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead} \tag{3}$$

Where $C_{total}$ is the total carbon density，$C_{above}$ is the carbon density in the aboveground biomass，$C_{below}$ is the carbon density in the underground biomass，$C_{soil}$ is the carbon density in soil, and $C_{dead}$ is the carbon density in dead organic matter。

(vi) Air quality regulation

Air quality regulation is vital to human health. Existing researches show that the plant community blades can remove gaseous and particulate air pollutants from the atmosphere, and the higher plant leaf area index, the greater the adsorption of pollutants in the air (Fontana et al., 2013). Therefore, leaf area index (LAI) can be used as an evaluation index of air quality regulation.

(vii) Habitat maintenance

Habitat can provide a place for species to grow, feed and reproduce, and by protecting habitat, species can be effectively conserved and regional biodiversity can be maintained. The habitat quality module of the InVEST model was used to evaluate the importance of habitat maintenance (Luo et al., 2020; Peng et al., 2018b). The model takes into account the relative influence distance of threat sources, distance between habitat patches and threat sources, sensitivity of habitat to threat factors, and degree of legal protection of land. The assessing results are the values between zero to one, indicating that the habitat maintenance is from poor to good.

## 2.3. Detection of ecosystem services bundles and their influencing factors

In this study, there are three major research steps: (1) using *k*-means to identify ecosystem services bundles; (2) carrying out PCA to clarify the main relationships among multiple ecosystem services; (3) performing Spearman correlation analysis to relate PCA results with social-ecological factors.

To identify ecosystem service bundles, *k*-means method was applied, which is widely used in the identification of ecosystem service clusters (Zhao et al., 2018; Roell et al., 2020). It can cluster continuous variables, so that the sum of inter-group deviation is maximized with the minimized intra-group deviation of the identified clusters. The number of clusters was determined using the Elbow Method based on the sum of Euclidean distances from the samples to the cluster center.

To spatially explore ecosystem services interactions of the whole study area, principal component analysis (PCA) was performed for the seven kinds of ESs (Chavent et al., 2014; Torralba et al., 2018). This multivariate analysis allows continuous variables to be recombined into a group of new orthogonal variables. According to the Kaiser-criterion (eigenvalues > 1), the first two PCA components were selected for interpretation of interactions among seven ESs.

To correlate ecosystem services interactions with social-ecological factors, the type of interactions between ESs in the study area were identified firstly, followed by Spearman correlation analysis with a set of social-ecological factors. As input variables, the values of the factor loadings of each sub-watersheds were used for the first two PCA components and seven social-ecological factors with important impacts on the ES interactions (Table 2). In details, the social-ecological factors were selected based on the social and ecological conditions of the study area including population density, nighttime light intensity, elevation derived from digital elevation model, precipitation, temperature, soil clay content, and soil sand content (Torralba et al., 2018).

**Table 2**. Basic characteristics of the social-ecological factors. Social-ecological factors are: Pop-population density; NTL-nighttime light intensity; DEM-average elevation; Pre-annual precipitation; Tem-annual temperature; CLAY-soil clay content ratio; SAND-soil sand content ratio.

| Social-ecological factors | Data sources | Spatial resolution | Temporal availability | Access link |
|---|---|---|---|---|
| Pop | LandScan | ~1km | 2000-2019 | https://www.satpalda.com/product/landscan/ |
| NTL | VIIRS | ~0.5km | 2013- | https://www.ngdc.noaa.gov/eog/viirs.html |
| DEM | USGS | 30m | / | https://www.usgs.gov/ |
| Pre | CRU | 0.5° | 1958- | http://www.cru.uea.ac.uk/about-cru |
| Tem | CRU | 0.5° | 1958- | http://www.cru.uea.ac.uk/about-cru |
| CLAY | ISRIC | 250m | 1950- | https://www.isric.org/ |
| SAND | ISRIC | 250m | 1950- | https://www.isric.org/ |

## 3. Results

### 3.1 Spatial patterns of ecosystem services

The results showed that ESs in the study area exhibited different spatial patterns (Fig. 2). The high-value areas of grain production were mainly distributed in the dry land and paddy land in the lower reaches of the study area. The high-value areas of water yield were mainly distributed in the water body area and the slope with low vegetation coverage. The high value areas of water purification were mainly distributed around the water body in the study area with high vegetation coverage. High-value areas of soil retention were mainly distributed in the middle reaches of the study area with abundant precipitation, and the land cover types were mainly forest land. The high-value areas of carbon storage were mainly distributed in watersheds with high forest land coverage in the study area. High-value areas for air quality regulation services were mainly distributed in the middle and lower reaches of the study area, where forest land and farmland coverage were relatively high. High-value areas of habitat maintenance in the study area were mainly distributed in the upper and middle watersheds with a large proportion of ecological land.

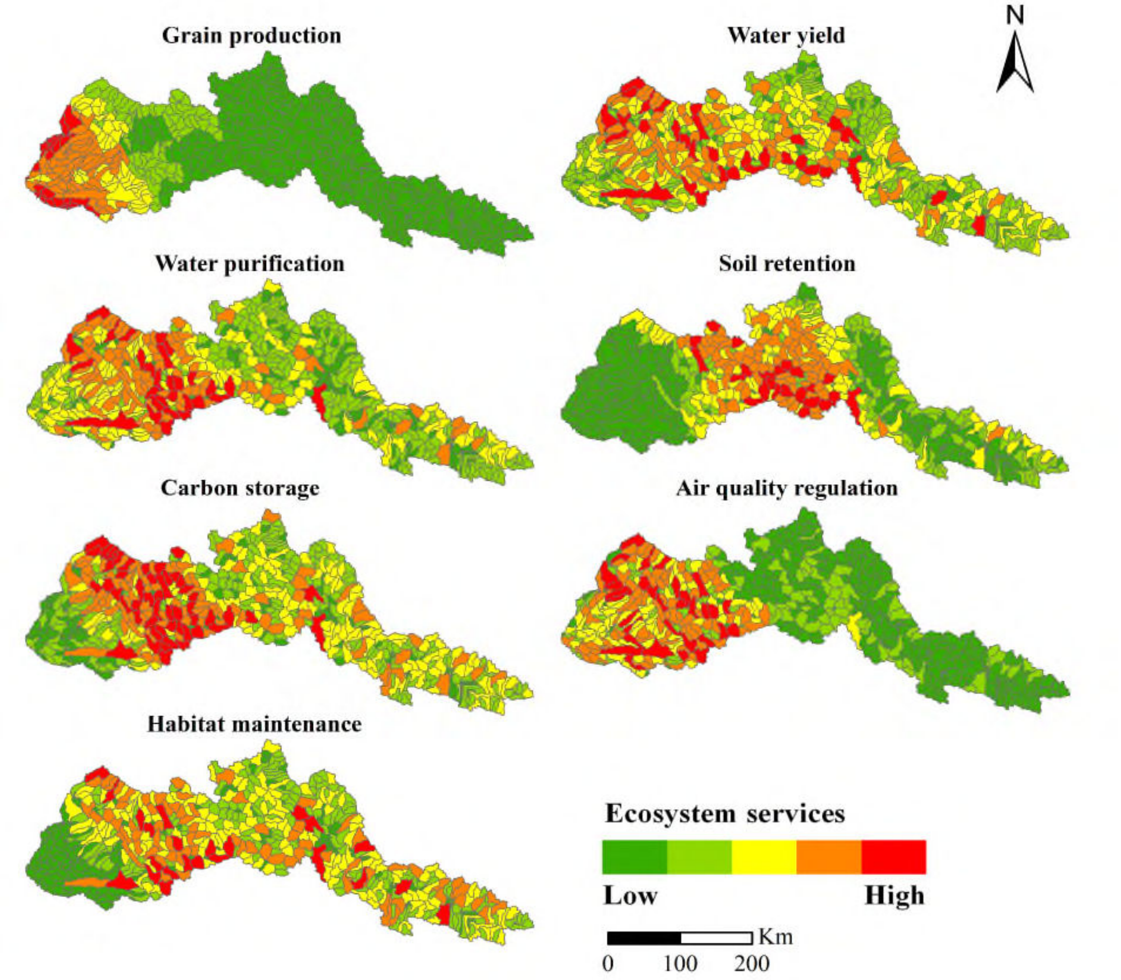

**Fig. 2.** Spatial patterns of ecosystem services provision in the Sutlej-Beas River Basin.

### 3.2 Ecosystem services interactions and associated social-ecological drivers

Two types of interaction among ESs were identified by comparing the ESs among 551 watersheds. The principal components analysis (PCA) reduced the seven ESs to two components, which explained 85.8% of the variability of the seven original indicators and had an eigenvalue larger than 1 (Table 3). The positive side of PCA1, identified as multifunctionality-related synergies, was associated on the positive side with water yield, water purification, carbon storage, soil retention, air quality regulation and habitat maintenance, but associated on the negative side with grain production. The positive side of PCA2, identified as grain production-related trade-offs, was associated on the positive side with grain production, water yield, water purification and air quality regulation, but associated on the negative side with soil retention, carbon storage and habitat maintenance (Fig. 3).

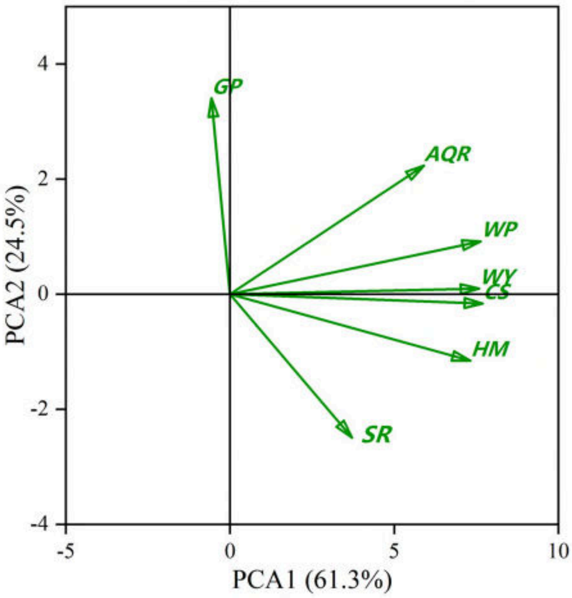

**Fig. 3.** Biplot of ecosystem services for the first two PCA axes (85.8% of the variability absorbed. ES indicators are: GP-grain production; WY-water yield; WP-water purification; SR-soil retention; CS-carbon storage; AQR-air quality regulation; and HM-habitat maintenance).

**Table 3.** Factor loadings derived from the PCA for multiple ecosystem services (Values in bold correspond to the factor for which the squared cosine is larger).

| | PCA1 Multifunctionality-related synergies | PCA2 Grain production-related trade-offs |
|---|---|---|
| Ecosystem services | | |
| Grain production | -0.070 | **0.892** |

| | | |
|---|---|---|
| Water yield | **0.943** | 0.025 |
| Water purification | **0.950** | 0.240 |
| Soil retention | 0.462 | **-0.653** |
| Carbon storage | **0.957** | -0.043 |
| Air quality regulation | **0.734** | 0.585 |
| Habitat maintenance | **0.910** | -0.303 |
| Eigenvalue | 4.294 | 1.716 |
| Variance explained (%) | 61.3 | 24.5 |
| Cumulative variance (%) | 61.3 | 85.8 |

Spearman's correlation analysis showed that both PCA1 and PCA2 had significant correlations with seven social-ecological factors (Table 4). Among them, population density, nighttime light intensity, annual precipitation, annual temperature and soil clay content ratio were positively correlated with PCA1 and PCA2. Moreover, with the increase of population density, nighttime light intensity, annual temperature and soil clay content ratio, the increase of PCA2 was higher than that of PCA1; but with the increase of annual precipitation, the increase of PCA1 was higher than that of PCA2. Contrarily, the average elevation and soil sand content ratio were negatively correlated with PCA1 and PCA2. The correlation coefficient between average elevation and PCA1 was -0.119, with -0.217 for that between soil sand content ratio and PCA1. However, for PCA2, the correlation coefficients of average elevation and soil sand content ratio were -0.777 and -0.624, respectively. Generally speaking, PCA1 behaved higher correlation with annual precipitation, while for the other social-ecological factors, there were stronger correlation with PCA2.

**Table 4.** Spearman correlation between ecosystem services interactions and social-ecological factors (Social-ecological factors are: Pop-population density; NTL-nighttime light intensity; DEM-average elevation; Pre-annual precipitation; Tem-annual temperature; CLAY-soil clay content ratio; and SAND-soil sand content ratio. Values in bold indicate stronger correlations).

| | PCA1<br>Multifunctionality-related synergies | PCA2<br>Grain production-related trade-offs |
|---|---|---|
| Pop | 0.408* | **0.654*** |
| NTL | 0.299* | **0.711*** |
| DEM | -0.119* | **-0.777*** |
| Pre | **0.484*** | 0.168* |
| Tem | 0.242* | **0.612*** |
| CLAY | 0.235* | **0.648*** |
| SAND | -0.217* | **-0.624*** |

### 3.3 Contrast of ecosystem services interaction among different bundles

The test result of Elbow Method showed that the inflection point of the curve appeared to be 4. As a result, four ES bundles were finally identified (Fig. 4). Each ES bundle was described according to their supply characteristics of multiple ESs as follows.

1) Ecological fragile area (Bundle 1). Compared with other ES bundles, ESs provision in Bundle 1 were generally at a lower level, especially for grain production and air quality regulation (Fig. 4). Watersheds in bundle 1 were mainly distributed in the negative direction of PCA1 and PCA2, and the average decomposition amounts of the watersheds in this bundle on the PCA1 and PCA2 axes were -0.422 and -0.518 respectively (Fig. 5, Table 5). The average elevation and soil sand content ratio in this bundle were the largest among the four bundles, and for all the other five social-ecological factors the average values were all the smallest among the four bundles (Fig. 6).

2) Habitat conservation area (Bundle 2). Except for grain production, all the other ESs had high provision in bundle 2, especially for habitat maintenance, carbon storage, water yield and water purification (Fig. 4). Watersheds in bundle 2 were mainly distributed in the direction of the positive axis of PCA1 and the negative axis of PCA2, and the average decomposition amounts of the watershed in this bundle on the PCA1 and PCA2 axes were 1.795 and -0.442, respectively (Fig. 5, Table 5). The average precipitation in Bundle 2 was the largest among the 4 bundles, and the average values of other social-ecological factors were between ecological fragile area and multifunctional area (Fig. 6).

3) Multifunctional area (Bundle 3). Except for soil retention, all the other ESs in Bundle 3 were at a relatively high level (Fig. 4). Watersheds in Bundle 3 were mainly distributed in the direction of the positive axis of PCA1 and PCA2, and the average decomposition amount of the watersheds in this bundle on the PCA1 and PCA2 axes were 0.900 and 1.090, respectively (Fig. 5, Table 5). The annual precipitation in this bundle was the 2nd highest amongst the bundles, only a little lower than that in habitat conservation area. For population density, nighttime light intensity, annual temperature, and soil clay content ratio, the average values were only lower than that in main grain-producing area (Fig. 6).

4) Main grain-producing area (Bundle 4). The dominant ES in Bundle 4 was grain production, and the average value of grain production in this bundle was much higher than that in other bundles, while the supply of regulating services in this bundle was much lower than in Bundle 2 and Bundle 3 (Fig. 4). Watershed in Bundle 4 was mainly distributed in the negative axis direction of PCA1 and the positive axis direction of PCA2, and the average decomposition amount of the watershed in this bundle on the PCA1 and PCA2 axis was -0.544 and 1.649, respectively (Fig. 5, Table 5). The main grain-producing area was in the lower plain of the study area. The average population density, nighttime light intensity, annual temperature and soil clay content ratio in this

bundle were the highest. The annual precipitation in this bundle was only higher than that in ecological fragile area (Fig. 6).

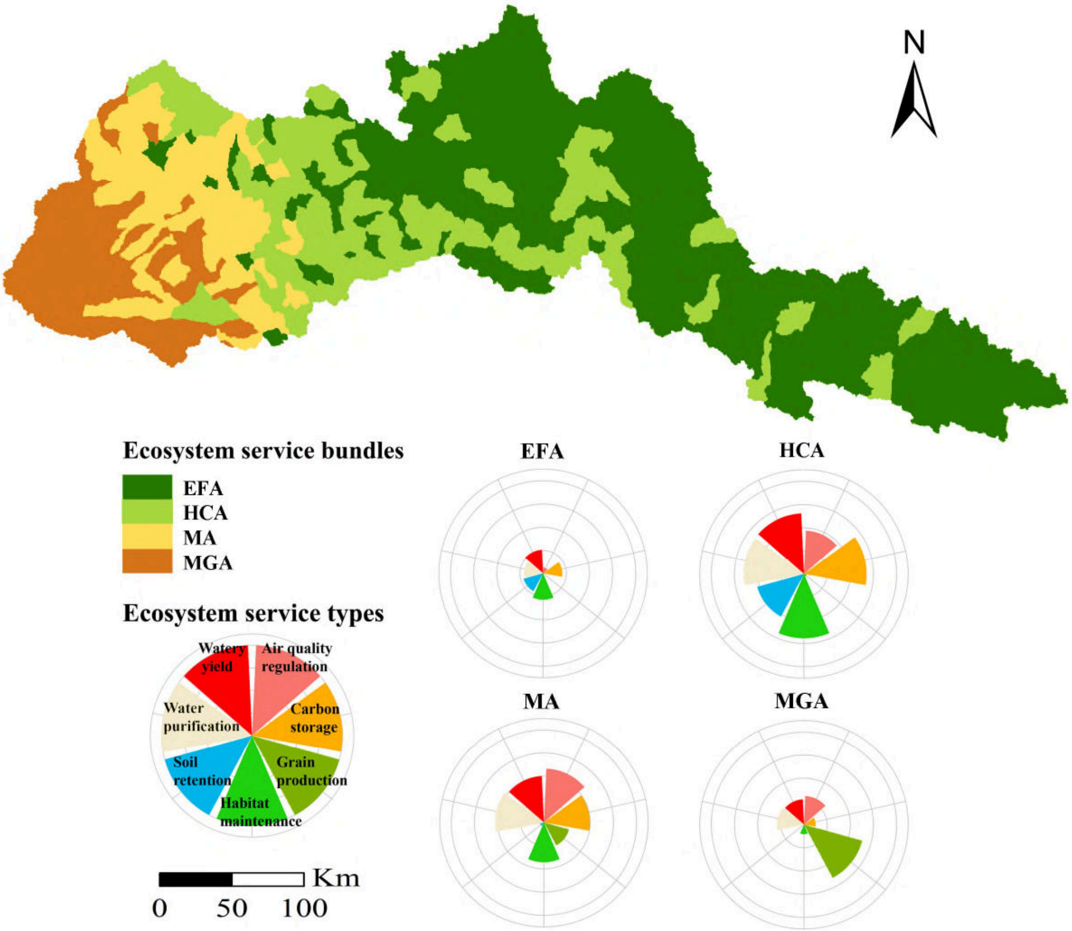

**Fig. 4.** Spatial pattern and rose diagrams of ecosystem services bundles (Ecosystem services bundles are: EFA-Ecological fragile area; HCA-Habitat conservation area; MA-Multifunctional area; and MGA-Main grain-producing area).

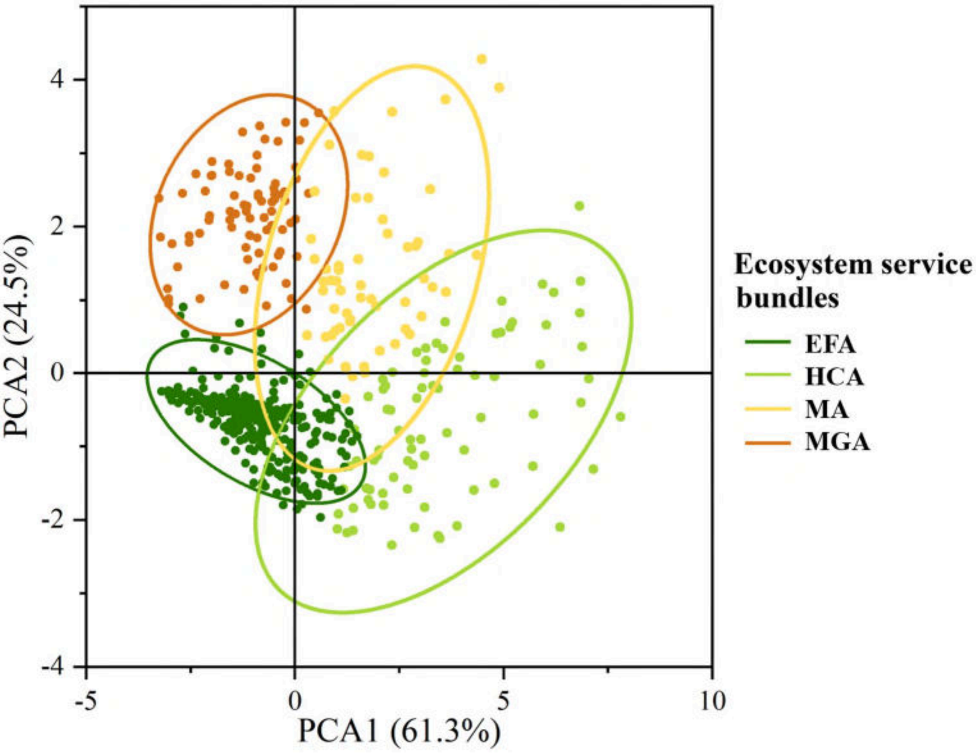

**Fig. 5.** Biplot of ES bundles for the first two PCA axes (85.8% of the variability absorbed. The color of labels indicate ecosystem services bundles and 95% confidence ellipses of bundles are added. Ecosystem services bundles are: EFA-Ecological fragile area; HCA-Habitat conservation area; MA-Multifunctional area; and MGA-Main grain-producing area).

**Table 5.** The mean values of PCA loadings of ecosystem services bundles.

| ES Bundles | PCA1 Multifunctionality-related synergies | PCA2 Grain production-related trade-offs |
|---|---|---|
| Ecological fragile area | -0.422 | -0.518 |
| Habitat conservation area | 1.795 | -0.442 |
| Multifunctional area | 0.900 | 1.090 |
| Main grain-producing area | -0.544 | 1.649 |

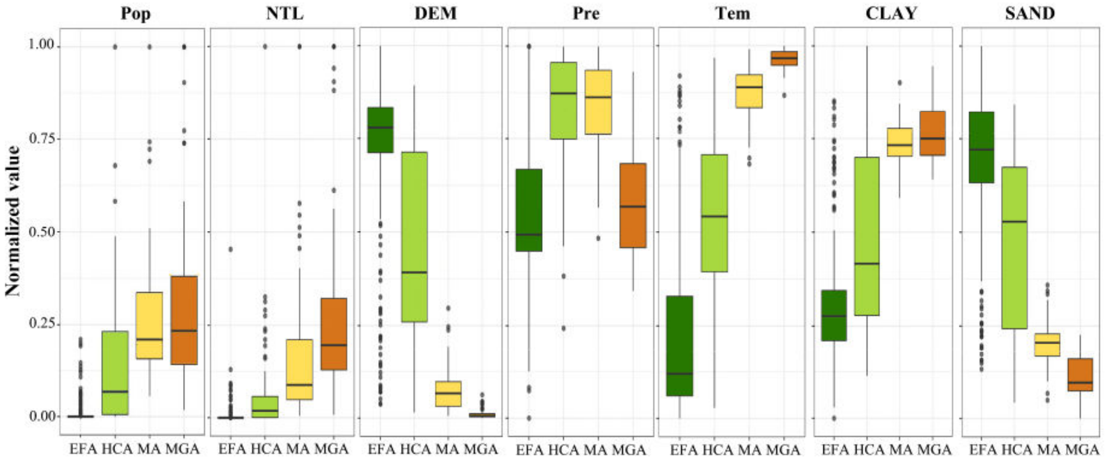

**Fig. 6.** Contrast of social-ecological properties in different ecosystem service bundles (Ecosystem services bundles are: EFA-Ecological fragile area; HCA-Habitat conservation area; MA-Multifunctional area; and MGA-Main grain-producing area. Social-ecological properties are: Pop-population; NTL-nighttime light; DEM-elevation derived from digital elevation model; Pre-annual precipitation; Tem-annual temperature; CLAY-soil clay content; and SAND-soil sand content).

## 4. Discussion

### 4.1 Interpretation of social-ecological impacts on ecosystem services interactions

Despite the increased research interest in ES interactions, more attentions are required on the underlying socioeconomic properties that affect ecosystem services and their interactions (Renard et al., 2015; Saidi et al., 2018; Torralba et al., 2018; Shen et al., 2020). This study quantified multiple ESs and investigated ESs trade-offs and synergies in the Sutlej-Beas River Basin. The relationship between the seven main social-ecological factors and the two main types of interaction between ESs reflected how social-ecological factors contributed to ES trade-offs and synergies in the study area (Table 3-4).

Quantification of ESs in the Sutlej-Beas River Basin indicated significant spatial variations among the upper, middle, and lower parts of the watershed (Fig. 2). These patterns were strongly correlated with the pronounced topography and human presence within the watershed. The results showed that ESs had distinctly different spatial patterns. For example, some were with high degrees of spatial homogeneity at watershed scale (e.g., grain production and soil retention), while others displayed greater spatial variability (e.g., habitat maintenance and water yield). The ES interactions were represented well by two principal components (85.8% of the variability explained). The first principal component was positively correlated with all the ESs except grain production. Thus, this principal component was mainly determined by multifunctional synergies among ESs. Contrarily, the second principal component was strongly positively correlated with grain production, with strongly negative correlation with soil retention. As a result, this principal component was mostly determined by trade-offs between grain production and other ESs, especially soil retention.

Correlation between ES interactions and social-ecological factors could provide further insights into the mechanisms driving these interactions. The results showed that all the factors were statistically significant (Table 4). The population density, nighttime light intensity, annual precipitation, annual temperature, and soil clay content ratio were positively correlated with the two types of ES interactions. Among them, except annual precipitation, all the others were more positively correlated with grain production-related trade-offs. Regarding the Sutlej-Beas River Basin, this finding was in correspondence with the characteristics of the low altitude areas in the middle and lower reaches of the whole watershed, which had higher annual temperature, well-developed soil texture, and more concentrated human population (Momblanch et al., 2019). Furthermore, the presence of large fertile floodplains and higher population density in the middle and lower reaches of the whole watershed, resulted in expansive farmland, providing high-level grain production (Main grain-producing area). Previous studies have also shown that grain production is largely incompatible with regulating services (Momblanch et al., 2019; Peng et al., 2019; Qiu et al., 2020). Therefore, in the case study area, grain production was at high level, while multiple regulating services were at low level, leading to grain production-related trade-offs in the lower part of the watershed.

Meanwhile, results indicated that average elevation and soil sand content ratio were negatively correlated with the two types of ES interactions, and there was stronger negative correlation with PCA2 than PCA1. This negative correlation was because those high-altitude areas had higher soil sand content ratio, which was not conducive to grain production (Peng et al., 2019). In the Sutlej-Beas River Basin, the high-altitude areas were mainly alpine grassland with high soil sand content ratio. The low temperature and poor soil texture were not conducive to grain production. Furthermore, these alpine grasslands comprised an important part of the ecological fragile area (Fig. 4), which were negatively associated with the two ES interactions (Table 5).

Furthermore, the results also showed that annual precipitation was more positively correlated with multifunctionality-related synergies (Table 4). Precipitation in the study area was mainly concentrated on the windward slope of the southwest monsoon (Momblanch et al., 2019), i.e. the middle reach (Habitat conservation area). The monsoon climate would lead to high soil moisture content in the middle reaches of the study area, and the vegetation coverage was good, which in turn made various regulating services at high level (Zhan et al., 2011). However, the proportion of cultivated land in this part was very low, resulting in a very low level of grain production service (Fig. 4). Because multiple regulating services were at a high level, the multifunctionality-related synergies were more obvious in this part (Table 5).

## 4.2 Implications and future research directions

This study provides a useful framework to explore spatial differentiation of ES trade-offs and synergies, which is important for both future research on ES interactions and sustainable landscape management. The provided insights can help decision-makers to generate enhancement of one or more ESs through adjusting specific social-ecological factors, without incurring unnecessary ES trade-offs (Raudsepp-Hearne et al., 2010; Hamann et al., 2015). Specific to the Sutlej-Beas River Basin, the findings suggested that ES trade-offs were most significant within the lower part of the watershed (e.g., habitat maintenance decreasing at the cost of increased grain production). In addition, these trade-offs were likely to be enlarged due to increasing urbanization (i.e. through positive correlation with population density and nighttime light intensity). Therefore, management efforts should be further focused on both social development and ecological conservation.

Furthermore, there are also some limitations in this study. First of all, as reported in other studies focusing on ecosystem services, the findings are greatly constrained by the available spatial data (Felipe-Lucia et al., 2014; Spake et al., 2017). For example, synergies and trade-offs among provisioning services and regulating services were identified in this study. As a contrast, cultural services were not considered due to spatial data limitation. However, cultural services and their interrelationships with regulating services as well as provisioning services are also important, because an awareness of cultural services will improve the sustainability of managed landscapes. Furthermore, more socio-ecological factors should be considered to refine the classification of synergies and trade-offs among ESs and to gain better insights into the mechanisms driving ESs interactions. In this study, only seven social-ecological factors were selected due to the limitation of data at watershed scale. To address this challenge, future studies could focus on specific areas within the watershed where spatial data were available for more social-ecological factors. It is also suggested to explore spatial patterns of ESs trade-offs and synergies over different scales in order to improve understanding of the spatial extent of the identified interactions and driving mechanisms. In addition to data limitations, the findings should be discussed with stakeholders to understand their attitudes towards ecosystem service trade-offs decisions so as to better meet the growing demands of local residents on natural ecosystems.

## 5. Conclusion

Understanding the linkages between ecosystem services interactions and social-ecological conditions is crucial for sustainable ecosystem management. In this study, the spatial differentiation of ESs trade-offs and synergies and their influencing factors were determined for one Himalayan River Basin of critical importance to water resource protection, agricultural development, and nature conservation. The results showed that multifunctionality-related synergies and grain production-related trade-offs were two dominant types of ESs interactions in the study area. The two interactions were positively correlated with five social-ecological factors (i.e. population density, nighttime light intensity, annual precipitation, annual temperature, and soil clay content ratio), with negative correlation with the other two (i.e. average elevation and soil sand content ratio). Additionally, four bundles among these ecosystem services were identified. Each of them represented a different type of interaction between ESs that were spatially clustered. The spatial clustering and distribution of these ESs bundles were strongly influenced by socio-ecological factors that varied from the high-altitude grasslands, the steep topography of the mid-altitude mountainous region, and the fertile low-altitude plains. This study provides a feasible way to explore spatial differentiation of ESs trade-offs and synergies as well as associated influencing factors, which could support for the decision-making of an integrated ESs trade-offs and synergies management at watershed scale.

**Acknowledgments:**

This work was supported by the National Natural Science Foundation of China (No. 41911530080) and the National Environment Research Council (NE/S01232X/1).

**Data Availability:**

The data underlying this research were obtained from other sources, as described in the methods section.

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