TRADE-OFFS AND SYNERGIES OF ECOSYSTEM SERVICE BUNDLES IN ECOLOGICALLY FRAGILE REGIONS: A CASE STUDY OF LUAN RIVER BASIN, CHINA

WANG, Y.[1] – WU, Z. Y.[1*] – BU, F.[2] – GAO, Q.[2]

[1]*College of Resources and Environmental Sciences, Hebei Minzu Normal University, Chengde 06700, China*

[2]*The Fourth Geological Team of Hebei Geology and Mineral Bureau, Chengde 06700, China*

**Corresponding author*
e-mail: wangye1991@hbun.edu.ccn

(Received 20th May 2024; accepted 23rd Sep 2024)

Abstract. The intricate interplay among various ecosystem services is crucial for effective ecosystem management and decision-making. Using the ecologically fragile Luan River Basin as a case study, which is pivotal for water conservation and ecological support in China's Beijing-Tianjin-Hebei region, we evaluated carbon storage, water yield, soil conservation, water retention, habitat quality, and food supply from 1990 to 2020. Employing clustering methods considering trade-offs and synergies, we identified ecosystem service bundles and examined their spatiotemporal variations. Results showed improvements in carbon storage, water yield, soil conservation, water retention, and habitat quality following the declines observed between 2000 and 2005, while food supply declined after 2005. Most services exhibited significant positive correlations, indicating synergies. Three ecosystem service bundles—"Ecological conservation synergy type," "Food supply trade-off type," and "Ecological balance type"—were delineated based on their values and proportions of synergies/trade-offs. Their dynamics were influenced by natural factors, ecological policies, and agricultural development. These findings underscore the need for tailored ecosystem management strategies in the Luan River Basin.
Keywords: *spatiotemporal analysis, ecosystem management, clustering methods, ecologically fragile, sustainable development*

Introduction

Ecosystem services are crucial resources for human survival and provide benefits that humans obtain directly or indirectly from ecosystems (Boyd et al., 2007; Swallow et al., 2009; Yang et al., 2018). These services are the environmental foundation for sustainable development. The Millennium Ecosystem Assessment (MEA) has revealed that 60% of global ecosystem services have been deteriorated, posing a significant threat to the sustainable development of human societies (Assessment, 2005). This deterioration can be attributed to the lack of understanding of the complex interactions among multiple ecosystem services and the lack of effective management (Leh et al., 2013; Xie et al., 2021). Therefore, there is a critical need to clarify the relationship and interaction mechanisms among ecosystem services, explore the aggregation mode of multiple services, and seek the synergistic development of ecological environmental protection and social economy for the scientific management of regional ecosystems (Li et al., 2017; Tallis et al., 2008; Vidal et al., 2013).

The study of relationships among ecosystem services requires a focus on bundles of ecosystem services, as well as their trade-offs and synergies. Ecosystem service bundles are formed by a range of temporally and spatially co-occurring ecosystem services (Cord et al., 2017; Dittrich et al., 2017). In ecosystem service bundles, trade-offs may

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2206_59775992

occur when increasing one service results in a decrease in the provision of another, while synergies may occur when multiple services are simultaneously enhanced (Kong et al., 2018; Rodriguez et al., 2006; Yang et al., 2015). The results of existing studies on ecosystem service indicate that there are mostly synergistic relationships between regulation services and cultural services within ecosystem service bundles, and trade-offs between supply services and regulation service (Lee et al., 2016). According to the global ecosystem services research literature, trade-offs are nearly three times more prevalent than synergies (Howe et al., 2014). Several studies have used different clustering methods to delineate ecosystem service bundles and have suggested ecosystem management strategies that aim to enhance synergy and reduce trade-offs, taking into account the perspective of service bundles (Birkhofer et al., 2015; Deng et al., 2016; Gret et al., 2017; Kong et al., 2018; Liu et al., 2019).

Currently, researchers have analyzed trade-offs and synergies among ecosystem services at national (Dittrich et al., 2017; Queiroz et al., 2015; Turner et al., 2014), regional (Raudsepp et al., 2010; Yang et al., 2015) and local (Crouzat et al., 2015; Wang et al., 2017; Yao et al., 2016) multi-scales, and have utilized ecosystem service bundles to identify patterns of multiple ecosystem services aggregation, with the aim of managing them simultaneously. Bai et al. (2021) concluded that there was a high level of spatial interactions among ecosystem services in Kentucky, USA, with 17 out of 21 possible pairs of ecosystem services showing significant correlation. Gan et al. (2022) quantified eleven ecosystem services in Shenyang, China, and identified land-use type as the main driver influencing interactions among ecosystem services. Zhang et al. (2021) proposed that the characteristics of ecosystem services are highly dependent on land use and land cover, and emphasized that well-informed land use planning could promote the implementation of efficient ecosystem service management in large-scale watersheds. Zhang et al. (2019) compared the overall changes in ecosystem services in the Beijing-Tianjin-Hebei region, China, under different ecosystem service protection policy scenarios and found that the integrated multi-service protection policy scenario was the most effective approach for protecting most of the ecosystem services, using an urban land use scenario simulation model. Wang et al. (2015) found that the conversion of natural wetlands to cropland in the Sanjiang Plain of China resulted in a decrease in carbon storage services but an enhancement of food supply services. Nevertheless, the majority of studies on ecosystem service bundles have only focused on identifying multiple ecosystem services, without further analyzing the trade-offs and synergies that exist among them within different service bundles. Ecosystem service bundles not only indicate the aggregation patterns of ecosystem services, but also reveal the interaction mechanisms that exist among them through the trade-offs and synergies within each bundle.

The Luan River Basin is a crucial component of the water conservation function and ecological environment support area in the Beijing-Tianjin-Hebei region of China (Xu et al., 2020). It irrigates nearly 21% of the irrigated areas in Hebei Province and supports about 20% of the population, accounting for nearly 30% of the province’s GDP. Therefore, the Luan River Basin plays an important role in supporting the economic and social development of Hebei Province, China. However, the Luan River Basin has faced ecological challenges such as water quality deterioration and soil erosion due to the accelerated urbanization and increased agricultural water demand (Qu et al., 2011). Furthermore, the basin is situated in a farming-pasturing interlock area with intricate ecosystem services, which makes it difficult to form an effective zoning management.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2206_59775992

In this study, we evaluated six key ecosystem services in the Luan River Basin from 1990 to 2020, including carbon storage, water yield, soil conservation, water retention, habitat quality, and food supply. The spatiotemporal variations of each ecosystem service bundle were analyzed to provide guidance for environmental protection and ecological restoration in the Luan River Basin. The objective of this study is to understand the interactions among these ecosystem services by identifying ecosystem service bundles and analyzing the trade-offs and synergies within them. This knowledge aims to support the development of targeted ecosystem management strategies tailored to the unique conditions of the Luan River Basin.

Materials and methods

Experimental site

The Luan River Basin is situated in the northeast part of the North China Plain, spanning between 39°10′-42°35′ N and 115°20′-119°15′ E (*Fig. 1*) (Wang et al., 2024). It originates from Fengning County and flows into the Bohai Sea in Leting County, covering a total length of approximately 877 kilometers and an area of 44,880 km^2. The landforms within the basin are diverse and complex, with the upper reaches being dominated by dam plateaus and mountainous hills in northern Hebei, the middle reaches by the Yanshan Mountains, and the lower reaches by the flat Hebei Plain. The terrain slopes from northwest to southeast, and there is a significant difference in climate between the north and the south. The climate varies significantly from north to south, with a transition from cold-temperate arid and semi-arid climate to warm-temperate semi-humid climate. The average annual temperature is between 1℃–11℃ and the average annual precipitation ranges from 400-800 mm. The Luan River Basin is characterized by interlaced zones of agriculture, pastoralism, and forestry, leading to complex relationships among ecosystem services (Zhao et al., 2022). The land cover mainly consists of cropland, grassland, and forest land, with small amounts of built-in land and bareland.

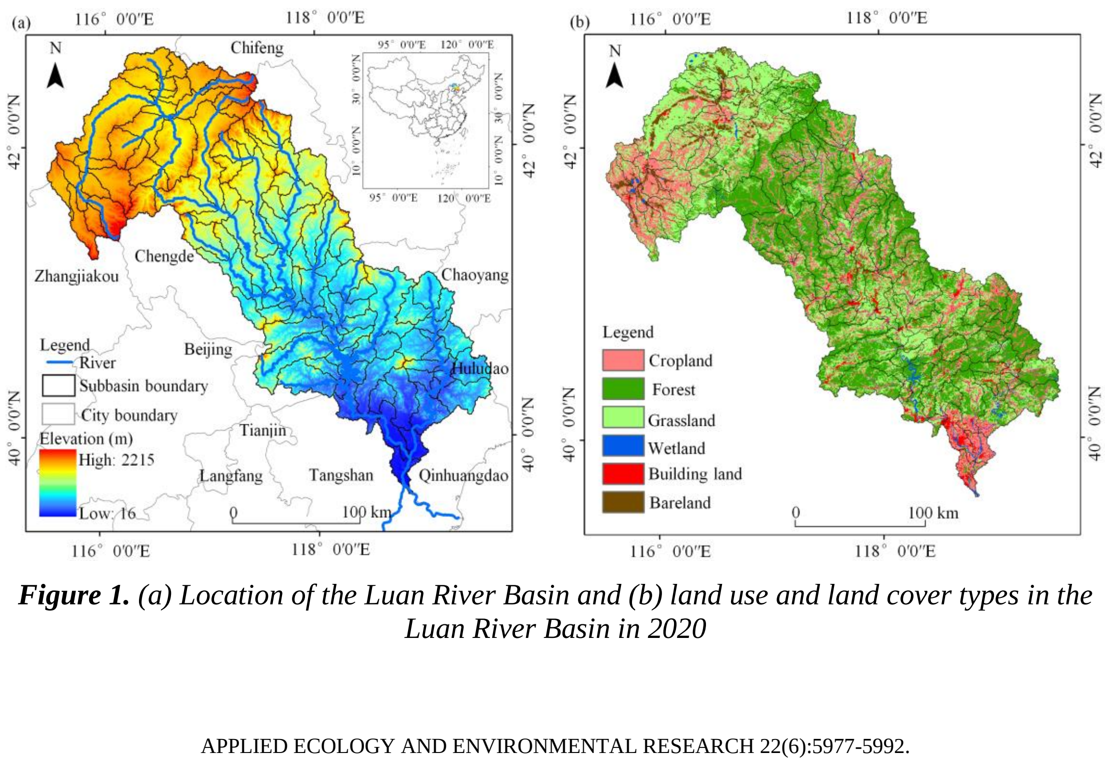

Figure 1. *(a) Location of the Luan River Basin and (b) land use and land cover types in the Luan River Basin in 2020*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2206_59775992

Data sources and processing

Land cover data with a spatial resolution of 30 m (7 periods, 1990, 2000, 2005, 2010, 2015, 2020) were downloaded from the Resource and Environmental Data Cloud platform (http://www.resdc.cn). The Digital Elevation Model (DEM) with a spatial resolution of 30 m were downloaded from the Geospatial Data Cloud (http://www.gscloud.cn) and filled in by Arcgis 10.0. Precipitation data were downloaded from the National Meteorological Information Center (http://data.cma.cn) and the National Tibetan Plateau Data Center (http://data.tpdc.ac.cn). Potential evapotranspiration data were obtained from the National Tibetan Plateau Data Center (http://data.tpdc.ac.cn). Precipitation and potential evapotranspiration raster data were overlaid and cropped by using ArcGIS 10.0. Soil data with a spatial resolution of 1 km, including soil texture, soil organic matter content and soil depth, were obtained from the Chinese soil characteristics in the Harmonized World Soil Database of Peking University Geographic Data Platform (https://geodata.pku.edu.cn). Average annual grain production data were obtained from the China Statistical Yearbook of the National Bureau of Statistics for Hebei Province, Liaoning Province, and Inner Mongolia Autonomous Region (http://www.stats.gov.cn/tjsj/ndsj). Geographic information data on administrative boundaries, rivers, roads and railroads were obtained from the National Geomatics Center of China (http://www.ngcc.cn/ngcc).

Carbon storage service

Carbon storage is an ecosystem service that involves the process of capturing atmospheric carbon dioxide through photosynthesis and storing it in plants and soils (Pache et al., 2021). The carbon storage module of the InVEST model was used to evaluate the cumulative calculation of carbon density based mainly on surface carbon density, soil carbon density, subsurface carbon density and dead carbon density (Tallis et al., 2008). The module formula is as follows:

$$C_t = C_a + C_s + C_b + C_d \tag{Eq.1}$$

where C_t is total carbon storage (t·hm^{-2}); and C_a, C_s, C_b, C_d are the carbon storage (t·hm^{-2}) in aboveground biomass, belowground biomass, soil, and dead biomass, respectively. The value of carbon storage was calculated while using the market value method.

Water yield service

Water yield refers to the amount of water that is available on the surface at a certain spatial and temporal scale (Yang et al., 2021). The InVEST model was used to evaluate the water yield by using the water production module based on the water balance principle. The model takes into account various parameters such as precipitation, evapotranspiration, soil depth, soil texture, and vegetation root depth of each grid cell. The module formula is as follows:

$$Y_{xj} = \left(1 - \frac{AET_{xj}}{P_x}\right) \times P_x \tag{Eq.2}$$

where Y_{xj} and AET_{xj} are the annual water yield and the actual evapotranspiration of the land cover type *j* in grid *x* in mm; and, P_x is the precipitation of Grid *x* in mm.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2206_59775992

Soil conservation service

Soil conservation is defined as the process of mitigating soil erosion through the actions of vegetation and the interception of sediments moving downslope (Gong et al., 2021). The soil conservation module of the InVEST model was employed to estimate the soil erosion amount in the study area using the Revised Universal Soil Loss Equation (RUSLE). The formulas of the module are as follows:

$$A = R \times K \times LS \times C \times P \quad \text{(Eq.3)}$$

$$RKLS = R \times K \times LS \quad \text{(Eq.4)}$$

$$SD = RKLS - A \quad \text{(Eq.5)}$$

where A is the estimated average soil loss ($t\cdot km^{-2}\cdot yr^{-1}$) per grid; $RKLS$ is the total potential soil loss (t) per grid; SD is the amount of soil retention (t); and, R is the rainfall erosivity ($MJ\cdot mm/(km^2\cdot h\cdot yr)$), which is calculated based on the average monthly and annual precipitations; K is the soil erodibility ($t\cdot km^2\cdot h/(km^2\cdot MJ\cdot mm)$), which is calculated based on relevant soil data; LS is the slope length gradient factor; C is the cover management factor; and, P is the support practice factor.

Water retention service

Water retention refers to the capacity of an ecosystem to retain water within the system at a specific spatial and temporal scale (Sun et al., 2022). The InVEST model is used to assess water retention based on the calculated water yield, as well as topographic index, soil saturation hydraulic conductivity, and flow coefficient. The formulas of the module are as follows:

$$Retention = \min\left(1, \frac{249}{Velocity}\right) \times \min\left(1, \frac{0.9TI}{3}\right) \times \min\left(1, \frac{Ksat}{300}\right) \times Y_x \quad \text{(Eq.6)}$$

where *Retention* is the water retention depth (mm); *Velocity* is the flow rate coefficient; *TI* is the topographic index; and $Ksat$ is the saturated hydraulic conductivity of the soil ($cm\cdot d^{-1}$).

Habitat quality service

Habitat quality is the degree of environmental suitability provided by the ecological system for the survival of organisms, which can reflect the quality of living environment for humans (Lin et al., 2017). Habitat quality is assessed using the habitat quality module of the InVEST model, which considers factors such as the distance and intensity of impact of threat factors. The formulas of the module are as follows:

$$Q_{xj} = H_j[1 - (\frac{D_{xj}^z}{D_{xj}^z + k^z})] \quad \text{(Eq.7)}$$

where Q_{xj} is the habitat quality index of the land cover type *j* in grid *x*; H_j is the habitat suitability of the land cover type j; D_{xj} is the habitat degradation index of the land cover

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2206_59775992

type j in grid x; $k$is the half-saturation constant, generally 1/2 of the maximum value of habitat degradation; z is the normalization constant.

Food supply service

The food supply of the districts and counties included in the Luan River Basin was spatialized based on the significant linear relationship between crops and NDVI (Gianquinto et al., 2011). This means that the distribution of food supply was determined according to the ratio of raster NDVI values to the total NDVI values of farmland. The formulas of the module are as follows:

$$G_x = G_{sum} \times \frac{NDVI_x}{NDVI_{sum}} \quad \text{(Eq.8)}$$

where G_x is the food supply in grid x (t); G_{sum} is the total food supply in the Luan River Basin (t); $NDVI_x$ is the normalized vegetation index in grid x; $NDVI_{sum}$ is the sum of NDVI of farmland in the Luan River Basin.

Trade-off and synergy assessment methods

In this study, the spatial trade-offs and synergies for each pair of ecosystem services were quantified by correlating the multiperiod raster data on ecosystem services using Pearson correlation analysis (Gou et al., 2021). A Pearson correlation coefficient above zero indicated synergy, while a coefficient below zero indicated a trade-off between ecosystem services. The strength of the synergy or trade-off was indicated by the coefficient’s proximity to 1 or -1, respectively. To provide a more intuitive description of trade-offs and synergies between ecosystem services, different color depths were used to represent the degree of trade-offs and synergies.

Ecosystem services bundle

Higher similarity subbasin units were grouped into the same bundle of ecosystem services by measuring their similarity and trade-offs and synergies. The K-means clustering analysis method was applied to obtain more stable clustering results, characterized by rapid calculation speed and high computational efficiency (Li et al., 2018). The optimal number of clusters was set to 3, and the operation parameters were configured with 200 initialization operations and a maximum number of 2000 iterations.

Results

Temporal and spatial variations of the ecosystem services

Figure 2 illustrates the spatial distribution of changes in ecosystem services in the Luan River Basin from 1990 to 2020. The areas that experienced increases in carbon storage, soil conservation, water retention, and food supply were mainly located in the upper reaches of the basin, where forest cover had been abundant and vegetation density was high. In contrast, the areas that experienced decreases were primarily found in the lower reaches, where land cover types were predominantly farmland and built-up areas,

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2206_59775992

with relatively high human activity intensity. Except for habitat quality, the annual average spatial distribution of changes in other services showed a significant north-south difference. This was due to the good ecological foundation in the northern part of the basin, while in the southern part, intensified human activities had led to issues such as reduced vegetation coverage and climate change, which significantly impacted ecosystem service functions (Li et al., 2016).

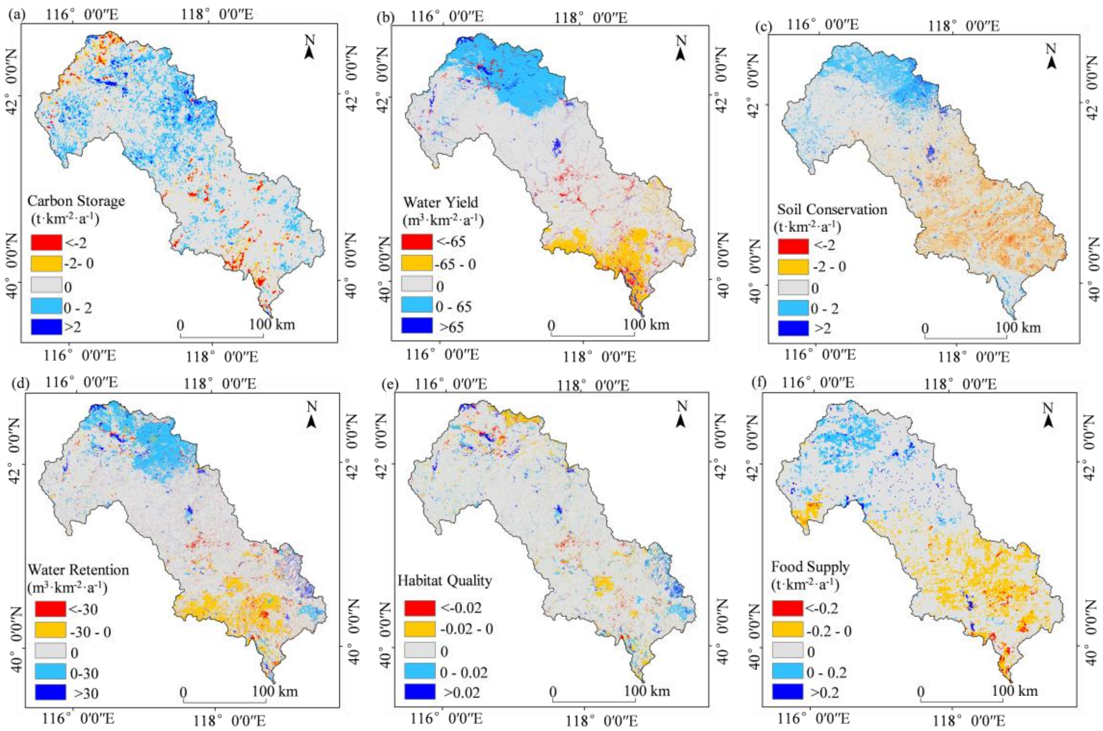

Figure 2. *Spatial variability of the values for individual ecosystem services in the Luan River Basin from 1990 to 2020: (a) carbon storage; (b) water yield; (c) soil conservation; (d) water retention; (e) habitat quality; and (f) food supply*

Carbon storage, water yield, soil conservation, water retention and habitat quality services rebounded after having reached the lowest value of services in 2000-2005 (*Fig.* 3*a*, *b*, *c*, *d*, *e*). This could have been due to an overall decrease in ecosystem services resulting from a sudden drop in precipitation in northern China from 1999-2003 (Chen et al., 2020). However, food supply services showed a significant declining trend after 2005 (*Fig. 3f*), which might have been related to the reduction of farmland area following the implementation of the policy of returning farmland to forest (grass) in 2000 (Gao et al., 2020).

Trade-offs and synergies among ecosystem services

Most of the ecosystem services were significantly correlated with each other (*Fig. 4a*). Among the 15 possible pairs of ecosystem services, 11 pairs exhibited significant correlations (Pearson coefficient; $p < 0.05$), and 8 of these pairs were highly significant (Pearson coefficient; $p < 0.01$).

Figure 4a showed that significant positive correlations existed among most ecosystem services, indicating synergies among them, while negative correlations

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2206_59775992

were observed between food supply and other ecosystem services, suggesting trade-offs among them. Water retention and water yield had the strongest significant positive correlation with a correlation coefficient of 0.84. Additionally, carbon storage and habitat quality, as well as soil conservation and water retention, also had high positive correlation coefficients exceeding 0.6. However, there was weak positive correlation between carbon sequestration and water yield, and between water yield and habitat quality, with correlation coefficients less than 0.2. The food supply was found to have extremely significant negative correlations with habitat quality and carbon storage, with correlation coefficients of -0.39 and -0.34, respectively. However, weak negative correlations were observed between food supply and water yield, as well as between water yield and soil conservation, with correlation coefficients less than 0.1. The area of synergy between water yield and water conservation was the largest, accounting for up to 63%, while the areas of synergy between soil and water conservation and water conservation, soil and water conservation and habitat quality, as well as water conservation and habitat quality, all exceeded 40%. The trade-off area between food supply and habitat quality was the largest, reaching 47% (*Fig. 4b, c*).

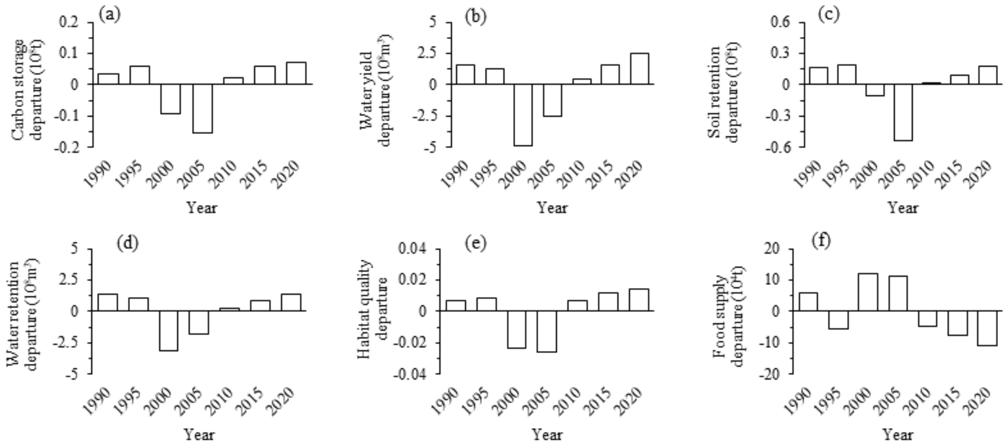

Figure 3. *Departure of the values obtained for individual ecosystem services in the Luan River Basin from 1990 to 2020: (a) carbon storage; (b) water yield; (c) soil conservation; (d) water retention; (e) habitat quality; and (f) food supply*

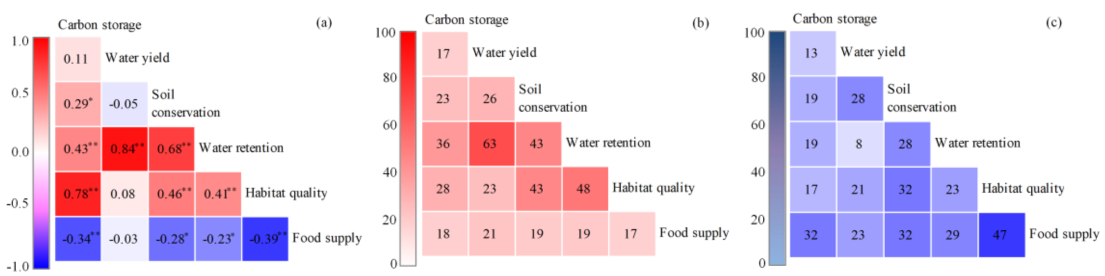

Figure 4. *(a) Matrix of Pearson correlations between different ecosystem services (* p < 0.05; ** p < 0.01). Red and blue colors indicate positive and negative correlations, respectively. The deeper the color, the higher the correlation. (b) Proportion of area for synergies between ecosystem services (%). (c) Proportion of area for trade-offs between ecosystem services (%)*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2206_59775992

The strong synergistic regions of carbon storage and soil conservation, carbon storage and water retention, water yield and water retention, soil conservation and habitat quality, and water retention and habitat quality covered the entire basin (*Fig. 5c, d, g, k, m*). The strong synergistic regions of soil conservation and water retention were mainly located in the upper and mid-lower reaches of the basin (*Fig. 5j*). Carbon storage and water yield, carbon storage and soil conservation, and water yield and habitat quality were dominated by weak synergistic regions, which were mainly distributed in the upper and middle reaches of the basin (*Fig. 5a, b, h*). The strong trade-off regions of carbon storage and food supply, and habitat quality and food supply covered the entire basin (*Fig. 5e, o*).

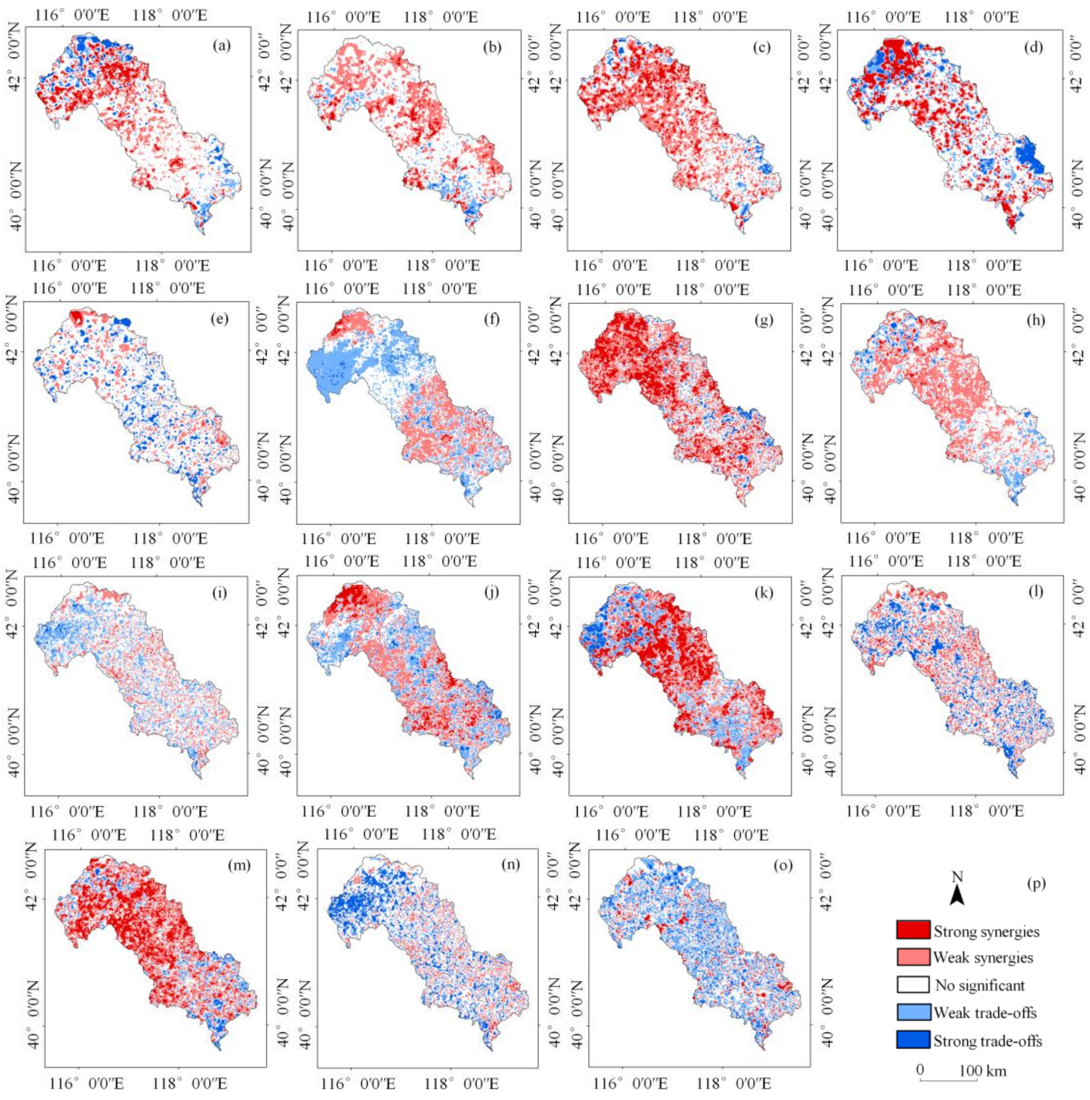

Figure 5. *Spatial distribution of trade-offs and synergies between ecosystem services: (a) carbon storage and water yield; (b) carbon storage and soil conservation; (c) carbon storage and water retention; (d) carbon storage and habitat quality; (e) carbon storage and food supply; (f) water yield and soil conservation; (g) water yield and water retention; (h) water yield and habitat quality; (i) water yield and food supply; (j) soil conservation and water retention; (k) soil conservation and habitat quality; (l) soil conservation and food supply; (m) water retention and habitat quality; (n) water retention and food supply; and (o) habitat quality and food supply*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2206_59775992

Soil conservation and food supply, and water retention and food supply were dominated by strong trade-off regions, which were mainly distributed in the lower reaches of the basin (*Fig. 5l, n*). The relationships between water yield and soil conservation, water yield and habitat quality, and soil conservation and water retention were not significant (*Fig. 5f, h, i*).

Ecosystem services bundles and variations

Bundles of ecosystem services identified using the K-means clustering for the Luan River Basin. The three ecosystem services bundles are represented by rosette diagrams. The diagrams are dimensionless, as they are based on normalized data for each service, and a larger petal length indicates the higher production of a particular service (*Fig. 6a, b, c*). Based on the ecosystem service value and the area proportion of synergies and trade-offs between ecosystem services (*Fig. 6d, e, f*), three ecosystem service bundles were identified as “Ecological conservation synergies type” (B1), “Food supply trade-offs type” (B2) and “Ecological balance type” (B3). In B1, carbon storage, water yield, soil conservation, water retention, and habitat quality were at high values with a dominant synergies of 44.36% of the mean area, while the mean area proportion of the trade-offs relationship was only 10.14%. In B2, both food supply and water yield were at high values with a dominant position of trade-off with a mean area proportion of 27.19%, compared to a mean area proportion of synergies of 16.67%. In B3, there is less difference and a balanced structure among ecosystem services, with the mean area proportion of synergies and trade-offs being 29.93% and 14.99%, respectively (*Fig. 6*).

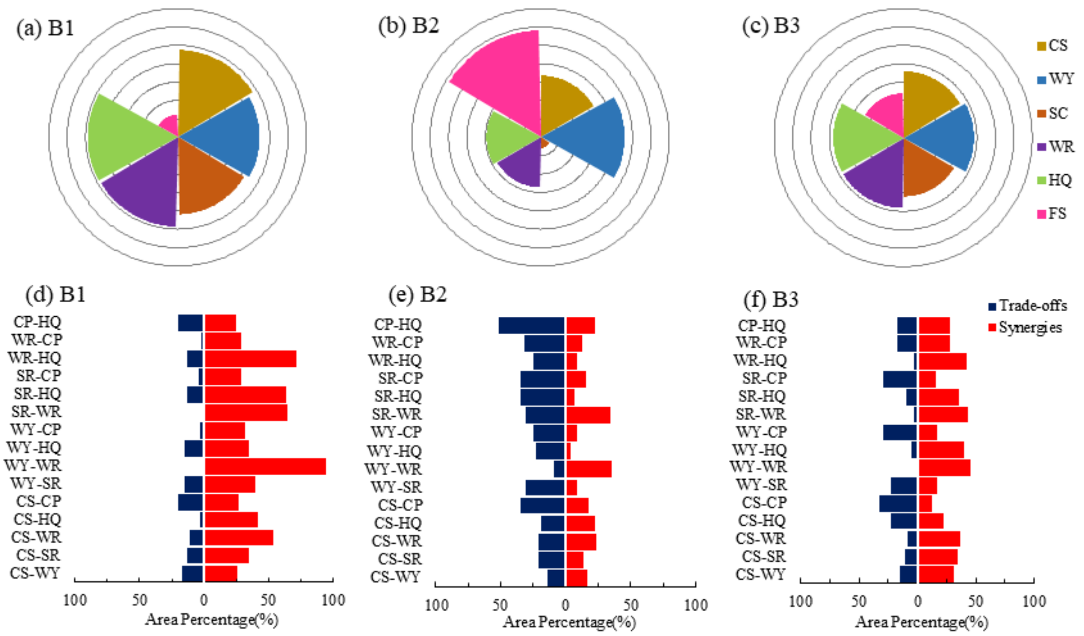

Figure 6. *Bundles of ecosystem services in the Luan River Basin, carbon storage (CS), water yield (WY), soil conservation (SC), water retention (WR), habitat quality (HQ), food supply (FS). (a) – (b) The three ecosystem services bundles are represented by rosette diagrams. (c) – (f) The proportion of trade-offs and synergies area for the three ecosystem services bundles are represented*

The 110 sub-basins in the Luan River Basin were classified into three groups based on the identified ecosystem services bundles. From 1990 to 2020, the spatial pattern of

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2206_59775992

B2 remained the most stable with an area change rate of -4.77%, followed by B1 (-23.38%) and B3 (80.04%). The range of B1 in the middle and lower reaches of the basin decreased before 2010, but became stable in the middle reaches and increased in the lower reaches after 2010. The range of B2 decreased in the upper reaches of the basin and increased in the lower reaches. The range of B3 increased in the overall basin before 2010 and decreased in the lower reaches after 2010 (*Fig. 7a-g*). The total area of B1 decreased to a minimum value of 2.05×10^4 km^2 in 2015 and showed a slight increase after that. The total area of B2 increased to the maximum value of 0.94×10^4 km^2 in 2005 and exhibited a decline after 2005. The total area of B3 continued to increase until 2015, after which it remained relatively stable (*Fig. 7h*).

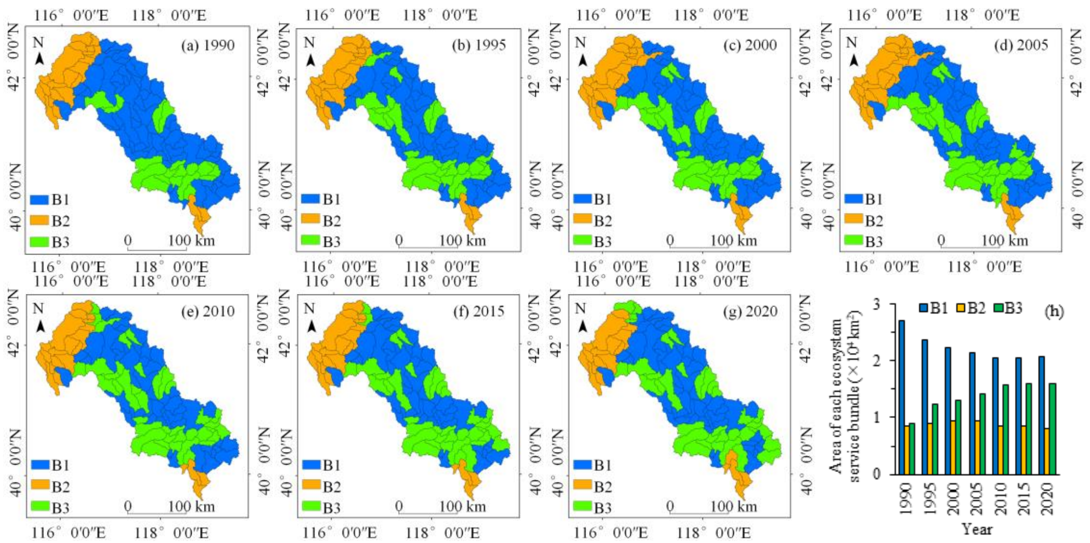

Figure 7. *(a–g) Spatial distribution of ecosystem services bundles in the Luan River Basin from 1990 to 2020. (h) Temporal distribution of ecosystem services bundles in the Luan River Basin from 1990 to 2020*

Discussion

Spatial and temporal characteristics of ecosystem services

Carbon storage, water yield, soil conservation, water retention, and habitat quality in the Luan River Basin had all improved, while food supply had declined. The variations in carbon storage in the farming-pastoral ecotone of northern China were assessed and showed an increasing trend in the upper and middle reaches of the Luan River basin (Liu et al., 2021). The spatial and temporal variations assessment of ecosystem services in the Beijing-Tianjin-Hebei region of China revealed that water yield, soil conservation, water retention, and habitat quality increased, with the high-value areas predominantly located in the forest ecological zone of the Luan River Basin (Pan et al., 2020). Quantification of ecosystem services in the Beijing-Tianjin-Hebei region of China revealed a decrease in food supply and an increase in habitat quality at the scale of the Luan River Basin (Xia et al., 2023). The above conclusions were consistent with the results of this study. The result of the Grain for Green Project in China after 2000 was an increase in vegetative cover, which enhanced carbon storage, soil conservation, water retention, and habitat quality (Deng et al., 2014, 2017; Liu et al., 2008; Song et al., 2014; Wang et al., 2016). The trend of increasing water yield in the middle and lower reaches of the Luan River Basin was

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2206_59775992

attributed to the increase in impervious surface area and the decrease in evapotranspiration and infiltration due to rapid urbanization (Jiang et al., 2017). Despite the improvement in agricultural technology and industrial structure (Wang et al., 2019), the total farmland area reduction in the Luan River basin, and the inefficiency of agricultural machinery in the mountainous regions of the upper and middle reaches of the basin resulted in a decreasing trend of food supply.

Ecosystem service bundles characteristics

The results of this study showed that there were mainly synergies between ecosystem services in the Luan River basin, while there were mainly trade-offs between food supply and other services. This was because food supply was mostly dependent on farmland area, whereas the high-value regions of other services were predominantly located in forests and grasslands, resulting in some competition between the two land use patterns (Yao et al., 2010). In terms of the characteristics of ecosystem service bundles, the “Ecological conservation synergies type” exhibited higher service value and positive synergies among multiple ecosystem services, which was important for ecosystem security in the Luan River basin. However, with the decrease in forest and grassland and the increase in built-in land, this type of region gradually transformed into other types of service bundles. Food supply trade-offs type” regions were characterized by strong food production and economic development but had low value in terms of carbon storage, soil conservation, water retention, and habitat quality. Consequently, the conflicts between ecological demands and food supply increased, leading to a region dominated by trade-offs. The “Ecological balance type” region was characterized by less difference in the value of each ecosystem service, and a more balanced proportion of trade-offs and synergies between ecosystem services. This region had the function of balancing ecological conservation and food supply. The areas with better natural backgrounds in the “Ecological balance type” regions were easily convertible to the “Ecological conservation synergy type” due to the implementation of ecological conservation policies. Similarly, they could also be transformed into the “Food supply trade-off type” due to agricultural economic development.

The effective management of ecosystems in the Luan River Basin

Ecosystem management in the Luan River basin required distinct measures based on different ecosystem service bundles. In regions characterized as “Ecological conservation synergy type”, strict implementation of the Grain for Green Project and other ecological recovery measures were necessary. One or more ecosystem services should be enhanced to promote the enhancement of other ecosystem services based on synergies. For regions classified as “Food supply trade-off type”, food supply services needed to be ensured through the conservation of farmland while minimizing trade-offs and maximizing synergies for other ecosystem services. In areas such as the plateau in the upper reaches and the plain in the lower reaches of the Luan River basin where the agricultural economy was growing rapidly, unreasonable cultivation needed to be reduced while enhancing carbon storage and water retention to prevent soil erosion caused by agricultural development. In “Ecological balance type” regions, the promotion of synergies between agricultural economic development and ecological conservation was necessary through the introduction of appropriate agricultural technologies and the improvement of soil conservation, water retention, and habitat quality by increasing vegetation cover.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2206_59775992

Conclusions

In this study, carbon storage, water yield, soil conservation, water retention, habitat quality, and food supply were assessed in the Luan River Basin from 1990 to 2020. Their spatiotemporal dynamics were analyzed, revealing distinct trends and changes. The spatial synergies and trade-offs among these ecosystem services were demonstrated and their bundles were identified through geographic clustering. The results showed that carbon storage, water yield, soil conservation, water retention, and habitat quality increased after reaching their lowest values in 2000-2005, while food supply exhibited a significant declining trend after 2005. Of the 15 possible pairs of ecosystem services, 11 pairs showed significant synergies, indicating high spatial interactions. The trade-offs were primarily between food supply and other services, whereas synergies were observed among most other ecosystem services. The study identified three types of ecosystem service bundles among the 110 sub-basins of the Luan River Basin. The findings showed that the areas with better natural backgrounds in the regions of the "Ecological balance type" can be readily converted to the "Ecological conservation synergy type" driven by ecological conservation policy, as well as to the "Food supply trade-off type" driven by agricultural economic development. As a result, differentiated management strategies based on the characteristics of different ecosystem service bundles should be adopted for ecological management in the Luan River Basin.

Acknowledgements. This research was funded the Higher Education Science and Technology Research Project for Hebei Province (No. BJK2023105), the Science and Technology Plan Project for Chengde City (No. 202205B005) and the Research Project on Social Science Development in Chengde City (No.20241009).

Data availability statement. The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

REFERENCES

[1] Millennium Ecosystem Assessment (2005): Ecosystems and human well-being: biodiversity synthesis. – World Resources Institute, Washington, DC.

[2] Bai, Y., Ochuodho, T. O., Yang, J., Agyeman, D. A. (2021): Bundles and hotspots of multiple ecosystem services for optimized land management in Kentucky, United States. – Land 10: 1-14.

[3] Birkhofer, K., Diehl, E., Andersson, J., Ekroos, J., Fruh, M. A., Machnikowski, F. (2015): Ecosystem services-current challenges and opportunities for ecological research. – Frontiers in Ecology and Evolution 2: 1-12.

[4] Boyd, J., Banzhaf, S. (2007): What are ecosystem services? The need for standardized environmental accounting units. – Ecological Economics 63: 616-626.

[5] Chen, Z. H., Zhang, J. (2020): The characteristics of late summer extreme precipitation in northern China and associated large-scale circulations. – International Journal of Climatology 40(12): 5170-5187.

[6] Cord, A. F., Bartkowski, B., Beckmann, M., Dittrich, A., Hermans, N. K., Kaim, A. (2017): Towards systematic analyses of ecosystem service trade-offs and synergies: main concepts, methods and the road ahead. – Ecosystem Services 28: 264-272.

[7] Crouzat, E., Mouchet, M., Turkelboom, F., Byczek, C., Meersmans, J., Berger, F. (2015): Assessing bundles of ecosystem services from regional to landscape scale: insights from the French Alps. – Journal of Applied Ecology 52: 1145-1155.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2206_59775992

[8] Deng, L., Liu, G. B., Shangguan, Z. P. (2014): Land-use conversion and changing soil carbon stocks in China's 'Grain-for-Green' Program: a synthesis. – Global Change Biology 20: 3544-3556.
[9] Deng, L., Liu, S. G., Kim, D. G., Peng, C. H., Sweeney, S., Shangguan, Z. P. (2017): Past and future carbon sequestration benefits of China's grain for green program. – Global Environmental Change-Human and Policy Dimensions 47: 13-20.
[10] Deng, X. Z., Li, Z. H., Gibson, J. (2016): A review on trade-off analysis of ecosystem services for sustainable land-use management. – Journal of Geographical Sciences 26: 953-968.
[11] Dittrich, A., Seppelt, R., Vaclavik, T., Cord, A. F. (2017): Integrating ecosystem service bundles and socio-environmental conditions—a national scale analysis from Germany. – Ecosystem Services 28: 273-282.
[12] Gan, S., Xiao, Y., Qin, K. Y., Liu, J. Y., Xu, J., Wang, Y. Y. (2022): Analyzing the interrelationships among various ecosystem services from the perspective of ecosystem service bundles in Shenyang, China. – Land 11: 1-17.
[13] Gao, Y. C., Liu, Z. H., Li, R. P., Shi, Z. D. (2020): Long-term impact of China's returning farmland to forest program on rural economic development. – Sustainability 12: 1-17.
[14] Gianquinto, G., Orsini, F., Fecondini, M., Mezzetti, M., Sambo, P., Bona, S. (2011): A methodological approach for defining spectral indices for assessing tomato nitrogen status and yield. – European Journal of Agronomy 35: 135-143.
[15] Gong, J., Zhang, J. X., Zhang, Y. X., Zhu, Y. H., Jin, T. T., Xu, C. X. (2021): Do forest landscape pattern planning and optimization play a role in enhancing soil conservation services in mountain areas of Western China? – Chinese Geographical Science 31: 848-866.
[16] Gou, M. M., Li, L., Ouyang, S., Wang, N., La, L. M., Liu, C. F. (2021): Identifying and analyzing ecosystem service bundles and their socioecological drivers in the Three Gorges Reservoir Area. – Journal of Cleaner Production 307: 1-14.
[17] Gret, R. A., Siren, E., Brunner, S. H., Weibel, B. (2017): Review of decision support tools to operationalize the ecosystem services concept. – Ecosystem Services 26: 306-315.
[18] Howe, C., Suich, H., Vira, B., Mace, G. M. (2014): Creating win-wins from trade-offs? Ecosystem services for human well-being: a meta-analysis of ecosystem service trade-offs and synergies in the real world. – Global Environmental Change-Human and Policy Dimensions 28: 263-275.
[19] Jiang, W. G., Deng, Y., Tang, Z. H., Lei, X., Chen, Z. (2017): Modelling the potential impacts of urban ecosystem changes on carbon storage under different scenarios by linking the CLUE-S and the InVEST models. – Ecological Modelling 345: 30-40.
[20] Kong, L. Q., Zheng, H., Xiao, Y., Ouyang, Z. Y., Li, C., Zhang, J. J. (2018): Mapping ecosystem service bundles to detect distinct types of multifunctionality within the diverse landscape of the Yangtze River Basin, China. – Sustainability 10: 1-16.
[21] Lee, H., Lautenbach, S. (2016): A quantitative review of relationships between ecosystem services. – Ecological Indicators 66: 340-351.
[22] Leh, M. D. K., Matlock, M. D., Cummings, E. C., Nalley, L. L. (2013): Quantifying and mapping multiple ecosystem services change in West Africa. – Agriculture Ecosystems & Environment 165: 6-18.
[23] Li, B. J., Chen, D. X., Wu, S. H., Zhou, S. L., Wang, T., Chen, H. (2016): Spatio-temporal assessment of urbanization impacts on ecosystem services: case study of Nanjing City, China. – Ecological Indicators 71: 416-427.
[24] Li, Y. C., Xie, Y. C. (2018): A new urban typology model adapting data mining analytics to examine dominant trajectories of neighborhood change: a case of metro Detroit. – Annals of the American Association of Geographers 108: 1313-1337.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2206_59775992

[25] Li, Y. J., Zhang, L. W., Qiu, J. X., Yan, J. P., Wan, L. W., Wang, P. T. (2017): Spatially explicit quantification of the interactions among ecosystem services. – Landscape Ecology 32: 1181-1199.
[26] Lin, Y. P., Lin, W. C., Wang, Y. C., Lien, W. Y., Huang, T., Hsu, C. C. (2017): Systematically designating conservation areas for protecting habitat quality and multiple ecosystem services. – Environmental Modelling & Software 90: 126-146.
[27] Liu, J. G., Li, S. X., Ouyang, Z. Y., Tam, C., Chen, X. D. (2008): Ecological and socioeconomic effects of China's policies for ecosystem services. – Proceedings of the National Academy of Sciences of the United States of America 105: 9477-9482.
[28] Liu, M. Z., Wang, Y. F., Pei, H. W. (2021): The changes of land use and carbon storage in the northern farming-pastoral ecotone under the background of returning farmland to forest (grass). – Journal of Desert Research 41: 174-182.
[29] Liu, Y. X., Lu, Y. H., Fu, B. J., Harris, P., Wu, L. H. (2019): Quantifying the spatio-temporal drivers of planned vegetation restoration on ecosystem services at a regional scale. – Science of the Total Environment 650: 1029-1040.
[30] Pache, R. G., Abrudan, I. V., Nita, M. D. (2021): Economic valuation of carbon storage and sequestration in Retezat National Park, Romania. – Forests 12: 1-14.
[31] Pan, M., Huang, L., Cao, W. (2020): Spatial and temporal variations in ecosystem services and its driving factors analysis in Jing-Jin-Ji region. – Acta Ecologica Sinica 40: 5151-5167.
[32] Qu, F. T., Kuyvenhoven, A., Shi, X. P., Heerink, N. (2011): Sustainable natural resource use in rural China: recent trends and policies. – China Economic Review 22: 444-460.
[33] Queiroz, C., Meacham, M., Richter, K., Norstrom, A. V., Andersson, E., Norberg, J. (2015): Mapping bundles of ecosystem services reveals distinct types of multifunctionality within a Swedish landscape. – Ambio 44: 89-101.
[34] Raudsepp, H. C., Peterson, G. D., Bennett, E. M. (2010): Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. – Proceedings of the National Academy of Sciences of the United States of America 107: 5242-5247.
[35] Rodriguez, J. P., Beard, T. D., Bennett, E. M., Cumming, G. S., Cork, S. J., Agard, J. (2006): Trade-offs across space, time, and ecosystem services. – Ecology and Society 11: 1-14.
[36] Song, X. Z., Peng, C. H., Zhou, G. M., Jiang, H., Wang, W. F. (2014): Chinese Grain for Green Program led to highly increased soil organic carbon levels: a meta-analysis. – Scientific Reports 4: 1-7.
[37] Sun, M. L., Hu, J., Chen, X. L., Lu, Y. H., Yang, L. X. (2022): Comparison of five models for estimating the water retention service of a typical Alpine wetland region in the Qinghai-Tibetan Plateau. – Remote Sensing 14: 1-19.
[38] Swallow, B. M., Sang, J. K., Nyabenge, M., Bundotich, D. K., Duraiappah, A. K., Yatich, T. B. (2009): Tradeoffs, synergies and traps among ecosystem services in the Lake Victoria basin of East Africa. – Environmental Science & Policy 12: 504-519.
[39] Tallis, H., Kareiva, P., Marvier, M., Chang, A. (2008): An ecosystem services framework to support both practical conservation and economic development. – Proceedings of the National Academy of Sciences of the United States of America 105: 9457-9464.
[40] Turner, K. G., Odgaard, M. V., Bocher, P. K., Dalgaard, T., Svenning, J. C. (2014): Bundling ecosystem services in Denmark: trade-offs and synergies in a cultural landscape. – Landscape and Urban Planning 125: 89-104.
[41] Vidal, L. B., Martinez, F. J., Picon, A. S., Pugnaire, F. I. (2013): Trade-offs between maintenance of ecosystem services and socio-economic development in rural mountainous communities in southern Spain: a dynamic simulation approach. – Journal of Environmental Management 131: 280-297.
[42] Wang, B. J., Tang, H. P., Xu, Y. (2017): Integrating ecosystem services and human well-being into management practices: insights from a mountain-basin area, China. – Ecosystem Services 27: 58-69.

[43] Wang, J. L., Zhou, W. Q., Pickett, S. T. A., Yu, W. J., Li, W. F. (2019): A multiscale analysis of urbanization effects on ecosystem services supply in an urban megaregion. – Science of the Total Environment 662: 824-833.
[44] Wang, S. A., Fu, B. J., Piao, S. L., Lu, Y. H., Ciais, P., Feng, X. M. (2016): Reduced sediment transport in the Yellow River due to anthropogenic changes. – Nature Geoscience 9: 38-41.
[45] Wang, Y., Liu, J., Zhang, L. R., Xue, Z. C., Yang, Y. (2024): Projecting the response of carbon sink potential to land use/land cover change in ecologically fragile regions. – Frontiers in Environmental Science 12: 1-17.
[46] Wang, Z. M., Mao, D. H., Li, L., Jia, M. M., Dong, Z. Y., Miao, Z. H. (2015): Quantifying changes in multiple ecosystem services during 1992-2012 in the Sanjiang Plain of China. – Science of the Total Environment 514: 119-130.
[47] Xia, C. Y., Zhao, J., Xue, F., Wang, C. Y., Zhou, J., Sun, T., Li, S., Zhang, N. (2023): Dynamic responses of ecosystem services to urbanization at multi-spatial scales in the Beijing-Tianjin-Hebei region the Beijing-Tianjin-Hebei region. – Acta Ecologica Sinica 43: 1-14.
[48] Xie, Z. L., Li, X. Z., Chi, Y., Jiang, D. G., Zhang, Y. Q., Ma, Y. X. (2021): Ecosystem service value decreases more rapidly under the dual pressures of land use change and ecological vulnerability: a case study in Zhujiajian Island. – Ocean & Coastal Management 201: 1-11.
[49] Xu, K. P., Wang, J. N., Wang, J. J., Wang, X. H., Chi, Y. Y., Zhang, X. (2020): Environmental function zoning for spatially differentiated environmental policies in China. – Journal of Environmental Management 255: 1-10.
[50] Yang, G. F., Ge, Y., Xue, H., Yang, W., Shi, Y., Peng, C. H. (2015): Using ecosystem service bundles to detect trade-offs and synergies across urban-rural complexes. – Landscape and Urban Planning 136: 110-121.
[51] Yang, S. Q., Zhao, W. W., Liu, Y. X., Wang, S., Wang, J., Zhai, R. J. (2018): Influence of land use change on the ecosystem service trade-offs in the ecological restoration area: dynamics and scenarios in the Yanhe watershed, China. – Science of the Total Environment 644: 556-566.
[52] Yang, X., Chen, R. S., Ji, G. X., Wang, C., Yang, Y. D., Xu, J. H. (2021): Assessment of future water yield and water purification services in data scarce region of Northwest China. – International Journal of Environmental Research and Public Health 18: 1-17.
[53] Yao, J., He, X. Y., Chen, W., Ye, Y., Guo, R. C., Yu, L. Z. (2016): A local-scale spatial analysis of ecosystem services and ecosystem service bundles in the upper Hun River catchment, China. – Ecosystem Services 22: 104-110.
[54] Yao, S. B., Li, H. (2010): Agricultural productivity changes induced by the sloping land conversion program: an analysis of Wuqi County in the Loess Plateau Region. – Environmental Management 45: 541-550.
[55] Zhang, D., Huang, Q. X., He, C. Y., Yin, D., Liu, Z. W. (2019): Planning urban landscape to maintain key ecosystem services in a rapidly urbanizing area: a scenario analysis in the Beijing-Tianjin-Hebei urban agglomeration, China. – Ecological Indicators 96: 559-571.
[56] Zhang, Y. S., Lu, X., Liu, B. Y., Wu, D. T., Fu, G., Zhao, Y. T. (2021): Spatial relationships between ecosystem services and socioecological drivers across a large-scale region: a case study in the Yellow River Basin. – Science of the Total Environment 766: 1-16.
[57] Zhao, L., Su, C. L., Liu, W. B., Xie, X. J. (2022): Understanding surface water-groundwater conversion relationship and associated hydrogeochemistry evolution in the upper reaches of Luan River Basin, North China. – Journal of Earth Science 35(3): 1010-1023.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2206_59775992