

Original Research

Spatial Heterogeneity and Factors Influencing Ecosystem Services in the Yimeng Mountainous Area

Xin Huang^{1,2}, Liang Wang^{1*}

¹Shandong Provincial Key Laboratory of Water and Soil Conservation and Environmental Protection, College of Resource and Environment, Linyi University, Linyi, China

²College of resources and environment, Anhui science and technology University, Chuzhou, China

Received: 23 December 2022

Accepted: 16 February 2023

Abstract

Understanding the influence mechanism of ecosystem services will provide some useful guides for practical ecological management. However, there is a limited understanding of the driving forces of ecosystem services, especially from the perspective of spatial heterogeneity. This study attempts to fill the gap in current research by examining the driving forces of the spatial heterogeneity of ecosystem services with an integrated spatial approach. The results show that ecosystem services in the Yimeng mountainous area are characterized by obvious spatial heterogeneity with uneven east-west distribution, that land use type is the dominant factor influencing the spatial heterogeneity of ecosystem services and that the combined effect of multiple drivers is more significant than the effect of any single driver in the interaction mechanism. This study will enrich the mechanistic analysis of the spatial heterogeneity of ecosystem services and provide important support for the optimization and sustainable development of ecosystem services in mountainous and hilly complex areas.

Keywords: ecosystem services, spatial heterogeneity, geodetector, Yimeng mountainous area

Introduction

Ecosystem services refer to resources that people derive from an ecosystem. Such resources include not only food, fresh water, and raw materials provided by the ecosystem for industrial and agricultural products but also support the earth's life system and maintain the biogeochemical and hydrological cycles, the equilibrium of atmospheric chemistry, biodiversity, and cleaning the

environment [1-4]. Therefore, ecosystem services are critical to human survival and development. At present, the global impact of climate change and human activities is increasing, the stability of ecosystems is decreasing, vulnerability is increasing, and service functions are gradually weakening [5], resulting in a series of serious challenges for ecosystem service management. The complex, diverse, and unique physical geography and social background characteristics of different regions make the spatial distribution of ecosystem services extremely heterogeneous, with large internal differences and obvious spatial variability, which further increases the difficulty of ecosystem service

*e-mail: wangliang.cn@163.com

management. How to identify the dominant drivers of regional spatial differentiation of ecosystem services and then formulate targeted spatial planning decisions for ecosystem services has become an urgent problem for ecosystem service management.

Currently, studies on the spatial heterogeneity of ecosystem services have been conducted to characterize the degree of spatial differentiation, for example, by using coefficients of variation and spatial autocorrelation indices to quantify the magnitude of spatial variation [6-7] or by using the concept of ecological "gradients" set by nature and man to analyse the spatial variation in ecosystem services along each gradient [8]. On the other hand, the relationship between ecosystem services and their influencing factors in different spatial locations was determined by regression modelling; for example, Ahmed et al. [9] and Hou et al. [10] used geographically weighted regression to analyse the relationship between ecosystem services such as water yield and net primary productivity and factors such as climate, land use, and landscape index. Although all of the above studies provide important reference values for regional ecosystem service management, there are some shortcomings that need further improvement. For example, when previous results are explored for drivers, most of them are mainly based on qualitative analysis [11-12] or mathematical statistics (correlation or regression analysis) [13-14]; the former has a strong subjectivity failing to achieve a more accurate quantitative analysis of drivers, while the latter is implemented with the assumption of a significant linear relationship between ecosystem services and drivers throughout the time series, while in reality, this relationship does not necessarily exist; meanwhile, both of the above methods do not analyse the synergistic effect of the interaction of factors on the driving effect of ecosystem service change; the Geodetector is a new statistical method to analyse the spatial heterogeneity of geographic phenomena based on the theory of spatial variance [15], which can not only reveal the driving forces behind geographic phenomena; but also quantify the individual driving factors and the interaction between factors, and can address the above two shortcomings, and it can provide a scientific basis and technical guide for ecosystem service management.

At the same time, it has also been pointed out that landscape heterogeneity directly influences species dynamics, community structure, and ecological processes in ecosystems and ultimately the expression of ecosystem services [16]. Landscape heterogeneity is more complex in mountainous areas, where the vertical gradient of the landscape formed by the combination of meteorological elements such as temperature and precipitation in the vertical direction varies with the spatial displacement of longitude and latitude in the horizontal direction. Accordingly, these features further enhance the spatial differentiation of ecosystem services. Although some scholars have studied the spatial and temporal evolution patterns of ecosystem

services and the degree of spatial differentiation, there is a lack of research on complex terrain areas, especially mountainous and hilly areas, and the understanding of their driving forces is more limited.

The present paper is a step in that direction and is based on the study of the Yimeng mountainous area. The two primary aims of our study were 1) to capture the spatial differentiation characteristics of each ecosystem service and 2) to identify the influencing factors of ecosystem services.

Material and Methods

Overview of Study Area

The Yimeng mountainous area is located in southern Shandong Province, China, at latitude 34°22'-36°23'N and longitude 116°34'-119°39'E, covering 27 counties (cities and districts) in Linyi City, Zibo City, Rizhao City, Jining City, and Zaozhuang City, with a total area of approximately 3.41×10^4 km² (Fig. 1). The climate type is a warm-temperate continental monsoon climate, with an average annual temperature of 12-14°C and an average annual rainfall of 700-900 mm, and summer precipitation accounts for more than 60% of the annual precipitation. The soil is mainly brown loam and brown soil, the terrain is high and mountainous in the northwest and low and hilly in the southeast, and the landform type is complex and diverse. The natural vegetation is mainly deciduous broad-leaved forest, but due to long-term human activities, natural vegetation is only seen in mountainous high-altitude areas and artificial vegetation is common in the secondary forest.

As a complete geographic unit, the study area is a typical composite ecosystem, offering important ecological services to the surrounding region. In addition, as a typical mountainous hilly region in China, the study area has significant spatial variability, making it an ideal site to study the spatially divergent characteristics of ecosystem services and the factors influencing them.

Data Sources and Processing

The data involved in this study include land use data, digital elevation models, soil data, normalized difference vegetative indices, meteorological data, and socioeconomic data. The data sources are shown in Table 1.

Methods of Analysis

Quantifying Ecosystem Services

According to the classification scheme of ecosystem services proposed by the United Nations Millennium Ecosystem Assessment [17], combined with the related

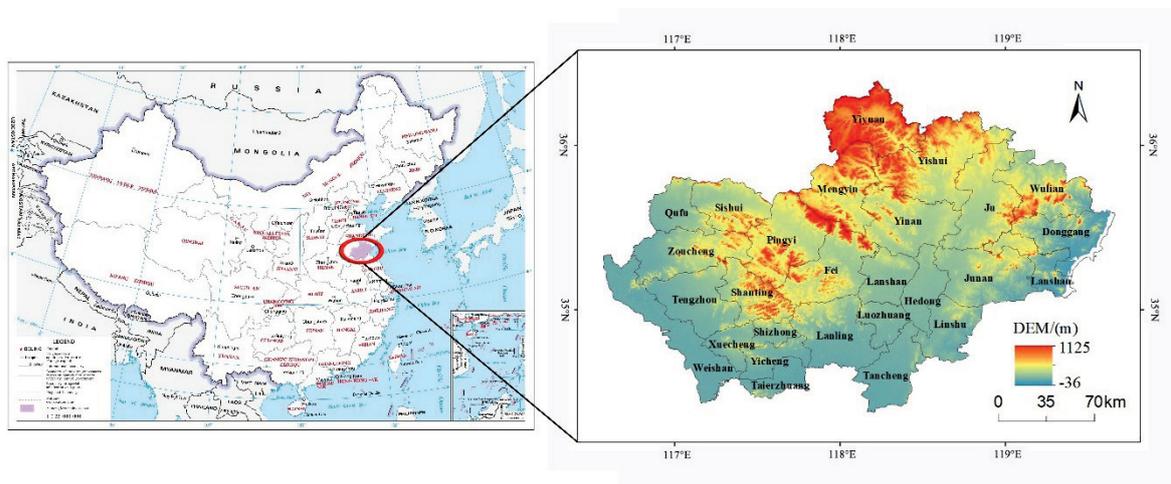


Fig. 1. Location map of the study area.

Table 1. Data sources table.

Type of data	Data sources	Website link
Land use data	Resource and Environment Science and Data Center	http://www.resdc.cn
Digital elevation model	Geospatial Data Cloud	http://www.gscloud.cn
Soil data	Scientific Data Center for Cold and Arid Regions	http://westdc.westgis.ac.cn/
Normalized difference vegetative index	American NASA website	http://lpdaac.usgs.gov
Meteorological data	National Meteorological Information Center	http://data.cma.cn
Socioeconomic data	Statistical Yearbook in Linyi city, Statistical Yearbook in Zibo city, Statistical Yearbook in Rizhao city, Statistical Yearbook in Jinig city, and Statistical Yearbook in Zaozhuang city	http://www.stats.gov.cn/

studies and the principles of importance and data availability, we selected food supply, soil conservation, water yield, carbon storage, and habitat quality as the key ecosystem services. These five ecosystem services were chosen because they are key ecosystem services provided to humans by the ecosystem in the study area. The region is an important part of the grain production base in China and is also the main area of high-quality vegetable, melon, and fruit production in Shandong Province. The region was listed as the Lu Central Mountains Soil Conservation Important Zone, which is one of China’s Key Ecological Function Areas [18] proposed by the People’s Republic of China to optimize the spatial distribution of land and resources and promote the construction of a sustainable ecological system. The main ecological function of this zone is soil conservation and water retention. The Yi River basin is also an important habitat for birds, aquatic plants, and animals. It is an important ecological protection area delineated in the National Outline of Ecological Environment Conservation [19], which is a program implemented to ensure sustainable development by protecting the ecological environment. In addition, large areas of forest and grassland vegetation

distributed in the region are also important carbon sources. However, a series of problems, such as food and water shortages, soil erosion, deforestation, and air pollution, are common ecological problems facing the study area and other regions. Therefore, a quantitative assessment of ecosystem services is urgently needed. Among the five ecosystem services considered in this study, data regarding food supply were directly extracted from the local Statistical Yearbooks at the district level and spatially allocated according to the normalized difference vegetative index for individual patches of land [20]. The Revised Universal Soil Loss Equation (RUSLE) [21-26] and Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) [27-33] were used to evaluate the other four ecosystem services. Table 2 shows the methods used to calculate ecosystem services in more detail.

Ecosystem Services Integrated Hotspot Areas

In this study, the hotspots of ecosystem services were considered to be those areas where the supply of each ecosystem service exceeded their respective mean values at the scale of the input raster. The hotspots of

Table 2. Methods for evaluating ecosystem services.

Ecosystem services	Methods	Algorithms ¹	Variables
Food supply	NDVI	$P_i = \frac{NDVI_i}{NDVI_t} \times P_t$	P_i is the food supply of raster i , $NDVI_i$ is the NDVI of raster i , $NDVI_t$ is the sum of NDVI, P_t is the total food supply.
Soil conservation	RUSLE	$A = R \times K \times LS \times (1 - C \times P)$	A is the average soil conservation, R is the rainfall erosion force factor, K is the soil erodibility factor, L is the slope length factor, S is the slope steepness factor, C is the vegetation cover and management factor, and P is the erosion control practice factor.
Water yield	InVEST	$Y_{xj} = \left(1 - \frac{AET_{xj}}{P_x}\right) \times P_x$	Y_{xj} is the annual water yield of raster x in the land use type j , AET_{xj} is the actual annual evapotranspiration of raster in the land use type j , P_x is the annual precipitation of raster x .
Carbon storage	InVEST	$C_z = C_{above} + C_{below} + C_{dead} + C_{soil}$	C_z is the total carbon storage, C_{above} is carbon storage in all living plant material above the soil, C_{below} is the carbon storage in the living root systems, C_{soil} is the carbon storage of soil, and C_{dead} is the carbon storage in the litter as well as lying and standing dead wood.
Habitat quality	InVEST	$Q_{xj} = H_j \left[1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z}\right)\right]$	Q_{xj} is the habitat quality of raster x in the land use type j , H_j is the suitability of land use type j for the species, D_{xj} is the threat level of raster x in the land use type j , z and k are scaling parameters.

¹ The meanings of different letters and specific calculation formulas can be found in the corresponding references.

food supply, soil conservation, water yield, carbon storage, and habitat quality were superimposed on the study area for each corresponding year to obtain the spatiotemporal distribution of the integrated hotspots for each year considered by the study. Based on the number of hotspots for individual ecosystem services, the hotspots were classified into six categories: class I hotspot area, class II hotspot area, class III hotspot area, class IV hotspot area, class V hotspot area, and non-hotspot area (Table 3).

Interrelationships among Ecosystem Services

In this study, we used GIS software combined with the Spearman correlation coefficient method to reveal the interaction of five ecosystem services in 2000, 2010, and 2018. The sampling interval was set to 1 km, and evenly distributed points were obtained in the study area. The raster maps of various ecosystem

services in 2000, 2010, and 2018 were then partitioned and sampled. The spatial distribution of trade-offs (i.e., inverse relationships) and synergies (i.e., mutual and positive relationships) between ecosystem services in the region was calculated by correlation analysis. Trade-offs between two ecosystem services were considered significant if their correlation coefficient was negative and significant at the 5% confidence level, whereas if the correlation coefficient was positive and significant, there was a synergistic and mutually beneficial relationship. If the correlation did not pass the significance test, then the relationship was considered compatible [36-37].

Identification of Driving Factors of Spatial Differentiation of Ecosystem Services

Spatial differentiation is one of the fundamental characteristics of geographic variables. Geodetector is a tool used to detect and exploit spatial

Table 3. Division of hotspot areas of ecosystem services in the Yimeng mountainous area.

Classes ²	Classification standard
Non-hotspot area	Not a hot spot for any ecosystem service
Class I hotspot area	There is one ecosystem service hotspot
Class II hotspot area	There are two ecosystem service hotspots that overlap
Class III hotspot area	There are three ecosystem service hotspots that overlap
Class IV hotspot area	There are four ecosystem service hotspots that overlap
Class V hotspot area	There are five ecosystem service hotspots that overlap

² Classification by reference to existing studies [34, 35].

differentiation. It is mainly used to analyse the driving forces, influencing factors, and multifactor interactions of various phenomena. This study considers each individual ecosystem service in the study area as the dependent variable and each factor affecting ecosystem services in the Yimeng mountainous area as the independent variable to explore which influencing factors drive each individual ecosystem service. The factor detector and interaction detector were used to analyse the extent to which each driving factor and factor combination explained the spatial heterogeneity of ecosystem services in the study area. The factor detection equation is expressed as follows:

$$q = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2} \tag{1}$$

where L is the stratification of the dependent variable or influence factor and N_h and σ_h^2 are the unit number and variance of layer h , respectively. N and σ^2 are the overall unit number and variance of the study area, respectively. The q -value measures the explanatory power of the factor in regard to y and is within the range $[0, 1]$. The larger the value is, the stronger the explanatory power of each factor.

The interaction detector principle is as follows:

Interaction detection is used to assess the degree of influence of different drivers combined on the dependent variable, and there are five types of interactions between any two factors. If $[q(X1 \cap X2)] < \text{Min}[q(X1), q(X2)]$ is nonlinearly weakened, $\text{Min}[q(X1), q(X2)] < [q(X1 \cap X2)] < \text{Max}[q(X1), q(X2)]$ is unidirectionally nonlinearly weakened, $[q(X1 \cap X2)] > \text{Max}[q(X1), q(X2)]$, undergoes two-factor enhancement, and $[q(X1 \cap X2)] = [q(X1) + q(X2)]$ is independent, then $[q(X1 \cap X2)] > [q(X1) + q(X2)]$ is nonlinearly enhanced.

The occurrence and development of ecosystem services are influenced and controlled by numerous factors; therefore, during the selection of the ecosystem service that drives the factors, the ecological environment and socioeconomic background of the Yimeng mountainous area were used as characteristics. Finally, annual precipitation, land use type, vegetation cover, altitude, and slope are selected as independent variables X , and food supply, soil conservation, water yield, carbon storage, and habitat quality are used as dependent variables Y in Geodetector. Since the

input variables of the Geodetector are required to be category data, first, we need to discretize continuous type variables. Combining the data discretization method and a priori knowledge [15, 38-40], the average annual rainfall is divided into 9 categories, and the land use types are divided into 6 categories: farmland, forestland, grassland, water bodies, construction land, and unused land. The vegetation cover is divided into 8 categories (≤ 0.3 , $>0.3 \sim 0.4$, $>0.4 \sim 0.5$, $>0.5 \sim 0.6$, $>0.6 \sim 0.7$, $>0.7 \sim 0.8$, $>0.8 \sim 0.9$, $>0.9 \sim 1$), altitude into 3 categories (≤ 500 m, $>500 \sim 1000$ m, $>1000 \sim 1500$ m), and slope into 6 categories ($\leq 5^\circ$, $>5 \sim 10^\circ$, $>10 \sim 15^\circ$, $>15 \sim 20^\circ$, $>20 \sim 25^\circ$, $>25^\circ$). The ecosystem service and driving factor classification values are assigned to the $1 \text{ km} \times 1 \text{ km}$ grid points as the operational data of Geodetector.

Results

Trends in Ecosystem Services Over Time in the Yimeng Mountainous Area

The results show that the food supply in the Yimeng mountainous area underwent an increasing trend from 2000 to 2018 (Table 4). Specifically, the annual average food supply in the study area increased from 634.677 t/km^2 in 2000 to 851.420 t/km^2 in 2018, which equates to an increase in the food supply of 34.15%. From 2000 to 2018, the food supply of all counties in the Yimeng mountainous area showed growth except Shizhong District and Lanshan District, which showed a slight decline, with Sishui County, Shanting District, Junan County, and Pingyi County increasing by 50.42%, 45.73%, 43.60%, and 43.11%, respectively (Fig. 2).

The annual average soil conservation in the Yimeng mountainous area in the three phases was 183.564 t/hm^2 , 253.595 t/hm^2 , and 253.927 t/hm^2 , respectively, from 2000 to 2018, which means that the annual average soil conservation increased by 38.33% (Table 4). From 2000 to 2018, the soil conservation of all counties in the Yimeng mountainous area showed growth except Tancheng County and Lanshan District, which showed a slight decline; 11 counties increased by more than 50%, with Shanting District, Weishan County, Tengzhou City, and Yiyuan County increasing by 88.32%, 87.93%, 79.16%, and 77.13%, respectively (Fig. 2).

The annual average in the Yimeng mountainous area in the three phases was 317.301 mm , 327.169 mm ,

Table 4. Ecosystem services in the Yimeng mountainous area from 2000 to 2018.

Year	Food supply (t/km ²)	Soil conservation (t/hm ²)	Water yield (mm)	Carbon storage (t)	Habitat quality
2000	634.677	183.564	317.301	1.036×10^8	0.476
2010	795.969	253.595	327.169	1.027×10^8	0.467
2018	851.420	253.927	511.378	1.012×10^8	0.425

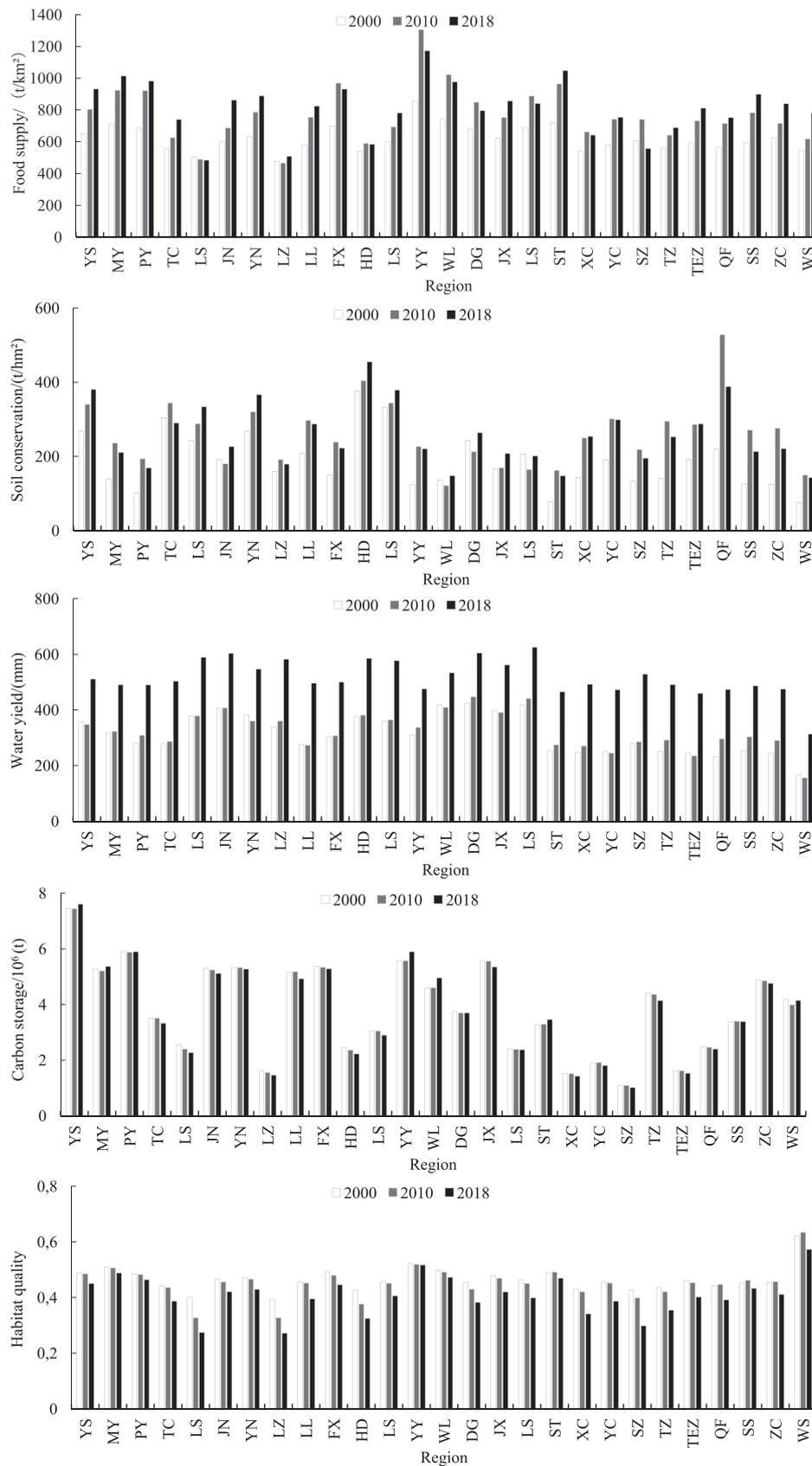


Fig. 2. The annual mean value of ecosystem services in the Yimeng mountainous area and each county in 2000, 2010 and 2018. Note: YS, Yishui County; MY, Mengyin County; PY, Pingyi County; TC, Tancheng County; LS, Lanshan District; JN, Junan County; LZ, Luozhuang District; LL, Lanling County; FX, Feixian County; HD, Hedong District; LS, Linshu County; YY, Yiyuan County; WL, Wulian County; DG, Donggang District; JX, Juxian County; LS, Lanshan District; ST, Shanting District; XC, Xuecheng District; YC, Yicheng District; SZ, Shizhong District; TZ, Tengzhou City; TEZ, Taierzhang District; QF, Qufu City; SS, Sishui County; ZC, Zoucheng City; WS, Weishan County.

and 511.378 mm, respectively, from 2000 to 2018, which equates to an annual average water yield increase of 61.16% (Table 4). All counties over the years also showed an increase, with a large overall change. Among them, Qufu City, Xuecheng District, Tengzhou City, Zoucheng City, and Sishui County increased by 103.86%, 97.92%, 96.01%, 92.60%, and 90.39%, respectively (Fig. 2).

The carbon storage in the Yimeng mountainous area showed a slight decreasing trend from 2000 to 2018. Specifically, the carbon storage in the study area decreased from 1.036×10^8 t in 2000 to 1.012×10^8 t in 2018, equivalent to a decrease of 2.32% (Table 4).

The trend of change over multiple years in all counties was divided into two types, with the northeastern counties mostly showing a decrease followed by an increase, and the southern counties mostly showing a year-by-year decrease. The carbon storage of Wulian County and Yiyuan County increased by 7.81% and 5.70%, respectively, while the carbon storage of Lanshan District and Luozhuang District decreased by 10.98% and 10.56%, respectively (Fig. 2).

During the study period, habitat quality dropped from 0.476 to 0.425, with habitat quality decreasing by 10.71% (Table 4). The trend of all counties over the years also showed a decline, with Lanshan District,

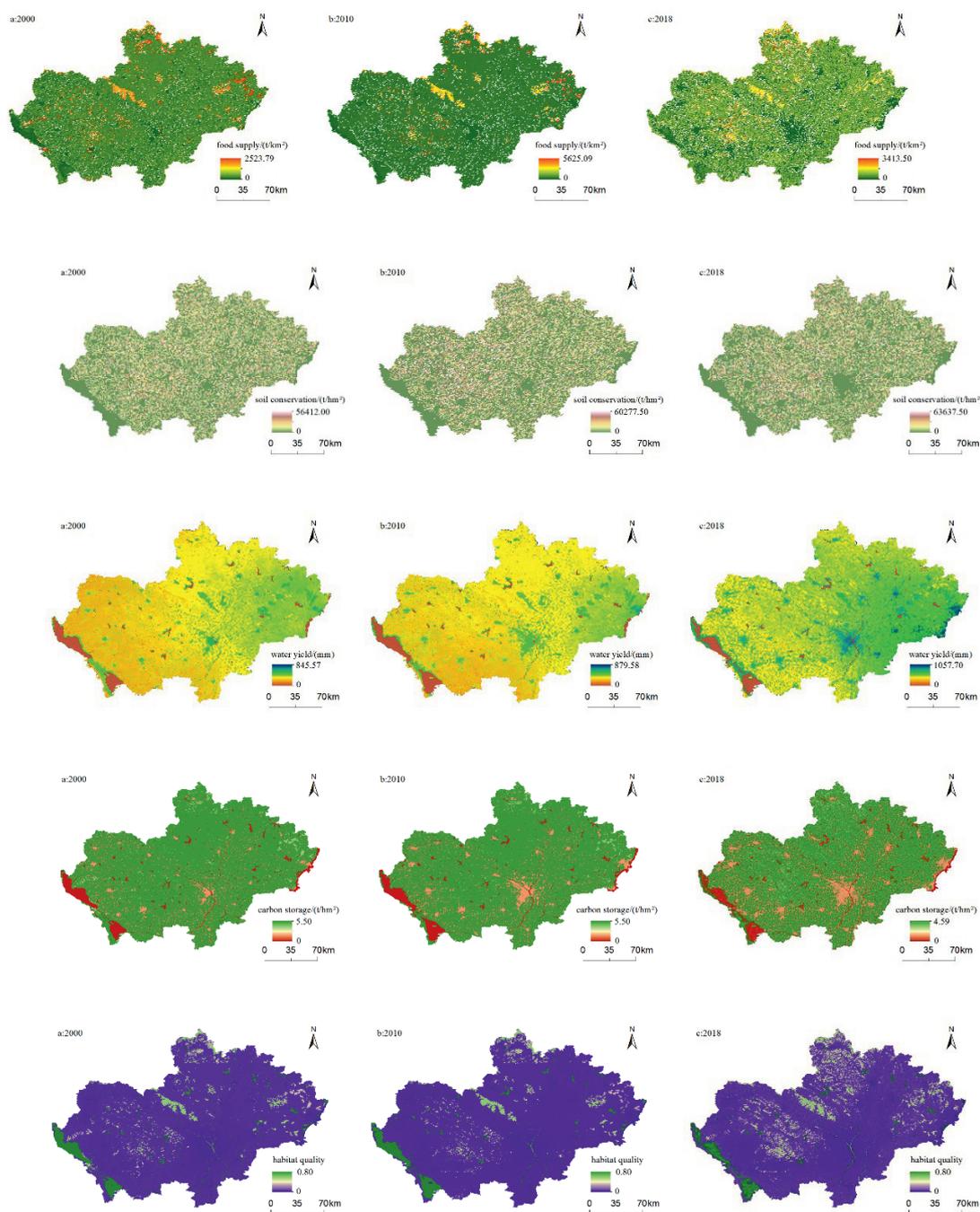


Fig. 3. Spatiotemporal distributions of ecosystem services in the Yimeng mountainous area from 2000 to 2018.

Luozhuang District, and Shizhong District declining by 31.67%, 30.96%, and 30.05%, respectively (Fig. 2).

Spatial Heterogeneity of Ecosystem Services in the Yimeng Mountainous Area

Spatial Heterogeneity of Individual Ecosystem Services

The spatial distributions of five ecosystem services in the Yimeng mountainous area in 2000, 2010, and 2018 are shown in Fig. 3. The results show that the multiyear average food supply in the Yimeng mountainous area was 760.689 t/km², and the spatial distribution of the food supply in the study area has obvious heterogeneity. The areas with high food supply were mainly distributed in the northeastern edge and northern regions of the Yimeng mountainous area, among which the food supply in Yiyuan County, Wulian County, and Shanting District was higher during the three periods. Specifically, the multiyear average food supply in the three counties reached 1111.982 t/km², 914.209 t/km², and 909.906 t/km². Moreover, the land use type of these three counties was mostly farmland or forestland; thus, it is reasonable to state that their food supply per unit area was relatively high. The areas with very low food supply were mainly distributed in Luozhuang District, Lanshan District, and Hedong District. Specifically, the multiyear average food supply in the three counties was only 483.182 t/km², 497.363 t/km², and 570.834 t/km². The reason is that this area mainly consisted of industrial land, and the area of farmland and forestland was relatively small.

The multiyear average of soil conservation in the Yimeng mountainous area was 230.362 t/hm², and the spatial distribution pattern of soil conservation was similar to that of the food supply. The areas with high soil conservation were mainly distributed in the mountainous areas, mainly in the central and northeastern regions of the study area. The abundant precipitation in the central and northeastern regions will make the area subject to higher rainfall-induced erosion than the southwestern region, while the areas with large slope changes in the mountainous areas will store a large amount of displaced soil. Furthermore, the mountainous area in this locality contains the majority of forested land in the Yimeng mountainous area and has a strong soil conservation capacity. The multiyear averages of soil conservation in Hedong District, Qufu City, and Linshu County were 411.519 t/hm², 378.528 t/hm², and 351.659 t/hm², respectively, which were significantly higher than the average. In contrast, the multiyear average of soil conservation in Weishan County and Shanting District in the southwestern region of the study area was only 122.623 t/hm² and 129.455 t/hm², respectively, which was significantly lower than the average. The multiyear average water yield depth in the Yimeng mountainous area was 385.283 mm, and the spatial distribution of water yield in the study area had obvious heterogeneity. The

water yield distribution is higher in the east and lower in the west, which coincides with the spatial rainfall pattern in the region. The areas with higher water yields were mainly located in the eastern region of the study area, such as Lanshan District, Donggang District, and Junan County, which have better hydrothermal conditions. The multiyear average water yield depth in the three counties reached 494.942 mm, 491.877 mm, and 471.976 mm, respectively, and the water yield was significantly higher than that in the western region. The areas with lower water yields were mainly located in the western region of the study area, such as Weishan County, Taierzhuang District, Yicheng District, and Shanting District. The multiyear average water yield depth in the three counties was only 212.253 mm, 312.758 mm, 322.441 mm, and 330.848 mm.

The spatial distribution of carbon storage in the Yimeng mountainous area also has clear heterogeneity, with a multiyear average of 1.025×10^8 t. The areas with high carbon storage were mainly located in the eastern and northern regions of the study area, where the climatic conditions are better than those in the western and central regions. Additionally, there are large areas of forestland in this area, while the western and central regions mainly contain water bodies and construction land. Among these locations, the carbon storage in Yishui County, Pingyi County, and Yiyuan County was higher during the three periods, with multiyear averages of 7.497×10^6 t, 5.892×10^6 t, and 5.679×10^6 t, respectively. The carbon storage in Shizhong District and Xuecheng District was lower in the three periods, with multiyear averages of 1.065×10^6 t and 1.482×10^6 t, respectively.

The multiyear average habitat quality in the Yimeng mountainous area is 0.456. The areas with high habitat quality mainly contained lakes and rivers or were in mountainous areas with good vegetation cover, such as those primarily found in the western and northern regions of the Yimeng mountainous area. Among these, the habitat quality in Weishan County, Yiyuan County, and Mengyin County was higher during the three periods, with multiyear average habitat quality values of 0.609, 0.520, and 0.501, respectively. The habitat quality in Luozhuang District and Lanshan District was lower during the three periods, with multiyear average habitat quality values of only 0.331 and 0.334, respectively.

Spatial Heterogeneity of Ecosystem Service Hotspot Areas

As shown in Fig. 4, the distribution of integrated hotspot areas of ecosystem services in the Yimeng mountainous area was basically consistent from 2000 to 2018, and the overlap ratio of the high-value areas of each ecosystem service, the proportion of the class V hotspot area and class IV hotspot area, was relatively low. Among them, the proportion of the class V hotspot area remained between 0.81% and 3.56% over the years,

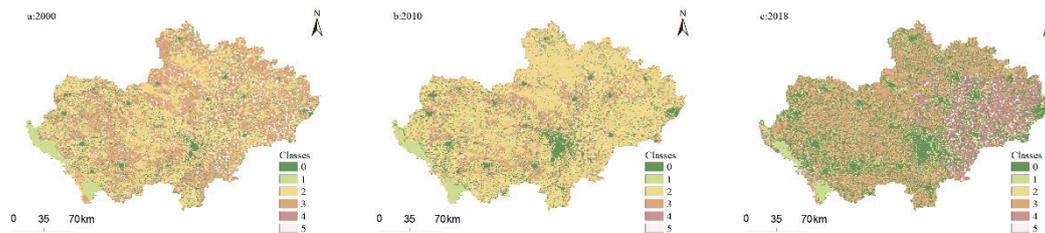


Fig. 4. Comprehensive hotspot area of ecosystem services in the Yimeng mountainous area.

Note: 0, 1, 2, 3, 4, and 5 represent the non-hotspot area, class I hotspot area, class II hotspot area, class III hotspot area, class IV hotspot area, and class V hotspot area, respectively.

and the areas were mainly distributed in the hilly area in the eastern region of the Yimeng mountainous area, where the vegetation conditions were significantly better than those in other regions. The percentage of the class IV hotspot area ranged from 1.90% to 17.46% over the years and was distributed in the periphery of the class V hotspot area in the eastern region of the Yimeng mountainous area. The percentages of the class III hotspot area and the class II hotspot area have remained between 18.62%-42.25% and 13.13%-64.54%, respectively, over the years. The proportion of overlapping low-value areas for each ecosystem service, class I hotspot area, is also low, with a proportion in the range of 4.92%-6.37% over the years, mainly in the western fringe of the Yimeng mountainous area. The percentage of the non-hotspot area, areas where no ecosystem service supply exceeds its average value, is between 7.26% and 18.24%, which are mainly located in the periphery of the class I hotspot area in the central and western region of the Yimeng mountainous area, which is mainly construction land and has significantly worse vegetation and good hydrothermal conditions than the eastern region of the Yimeng mountainous area.

Interrelationships among Ecosystem Services

The interactions between various ecosystem services in the Yimeng mountainous area were different, and the trade-offs and synergistic relationships changed over time. Trade-offs and synergistic relationships existed in 10 groups among five functions over the three periods of time. In 2000, there were two pairs and eight pairs; three pairs and seven pairs in 2010; and three pairs and seven pairs in 2018 (Table 5).

The trade-off relationships changed considerably between 2000 and 2018. These relationships, ranked from strongest to weakest, in 2000 were water yield-habitat quality and water yield-carbon storage. The ranking in 2010 was water yield-habitat quality, soil conservation-water yield, and water yield-carbon storage. In 2018, the ranking was water yield-carbon conservation, water yield-habitat quality, and soil conservation-water yield.

The synergies between 2000 and 2018 also changed. These relationships, ranked from strongest to weakest, in 2000 were food supply-carbon storage, food supply-soil conservation, soil conservation-carbon storage, carbon storage-habitat quality, food supply-habitat quality, soil conservation-water yield, food supply-water

Table 5. Correlation coefficient of ecosystem services in the Yimeng mountainous area

Ecosystem services	2000	2010	2018
Food supply & Soil conservation	0.560**	0.791**	0.392**
Food supply & Water yield	0.150**	0.188**	0.271*
Food supply & Carbon storage	0.572**	0.720**	0.691**
Food supply & Habitat quality	0.176**	0.196**	0.161**
Soil conservation & Water yield	0.164**	-0.153**	-0.138**
Soil conservation & Carbon storage	0.234*	0.140*	0.175**
Soil conservation & Habitat quality	0.130**	0.104**	0.115**
Water yield & Carbon storage	-0.116**	-0.141**	-0.274**
Water yield & Habitat quality	-0.188**	-0.257**	-0.160*
Carbon storage & Habitat quality	0.185**	0.108**	0.228**

** at 0.01 level, * at 0.05 level.

yield, and soil conservation-habitat quality. Those in 2010 were food supply-soil conservation, food supply-carbon storage, food supply-habitat quality, food supply-water yield, soil conservation-carbon storage, carbon storage-habitat quality, and soil retention-habitat quality. In 2018, the ranking was food supply-carbon storage, food supply-soil conservation, soil conservation-water yield, carbon storage-habitat quality, soil conservation-carbon storage, food supply-habitat quality, and soil conservation-habitat quality.

From the above analysis, it can be seen that relationships between soil conservation-water yield, water yield-carbon storage, and water yield-habitat quality were overall seen to be negative from 2000 to 2018. The relationships of food supply-soil conservation, food supply-water yield, food supply-carbon storage, food supply-habitat quality, soil conservation-carbon storage, soil conservation-habitat quality, and carbon storage-habitat quality were positive, among which the synergistic relationships of food supply-water yield strengthened over time. Overall, synergistic relationships were the main relationships among the five ecosystem services in the Yimeng mountainous area.

Identification of Driving Factors of Spatial Differentiation of Ecosystem Services in the Yimeng Mountainous Area

One Factor Attribution of the Spatial Heterogeneity of Ecosystem Services

All the ecosystem services in the Yimeng mountainous area show obvious spatial heterogeneity,

which is mostly the result of the combination of natural factors and human activities. In this study, the contribution of each driving factor to the spatial heterogeneity of different ecosystem services in the Yimeng mountainous area over different years was obtained with the help of the factor detector and interaction detector within the Geodetector. From Fig. 5, it can be seen that the explanatory power of each driving factor for ecosystem services in the Yimeng mountainous area has a strong consistency between 2000, 2010, and 2018; therefore, this study follows the attribution analysis of the factors influencing the ecosystem services in the Yimeng mountainous area using 2018 data as an example.

According to the factor detector, the results (q value) show the influence of each factor on various ecosystem services in the Yimeng mountainous area. The order of influencing factors of food supply was land use type (0.533)>annual precipitation (0.417)>vegetation cover (0.286)>altitude (0.165)>slope (0.025). From the q value of each factor to food supply, land use type and annual precipitation were the main influencing factors with an explanatory power of more than 40%. Vegetation cover and altitude were the secondary influencing factors, and slope had less influence on it.

The order of the factors influencing soil conservation was land use type (0.435)>annual precipitation (0.402)>vegetation cover (0.231)>altitude (0.092)>slope (0.034). Among them, land use type and annual precipitation played a dominant role, followed by vegetation cover, which had strong explanatory power. The p value for slope is too large, indicating that the relationship is not significant.

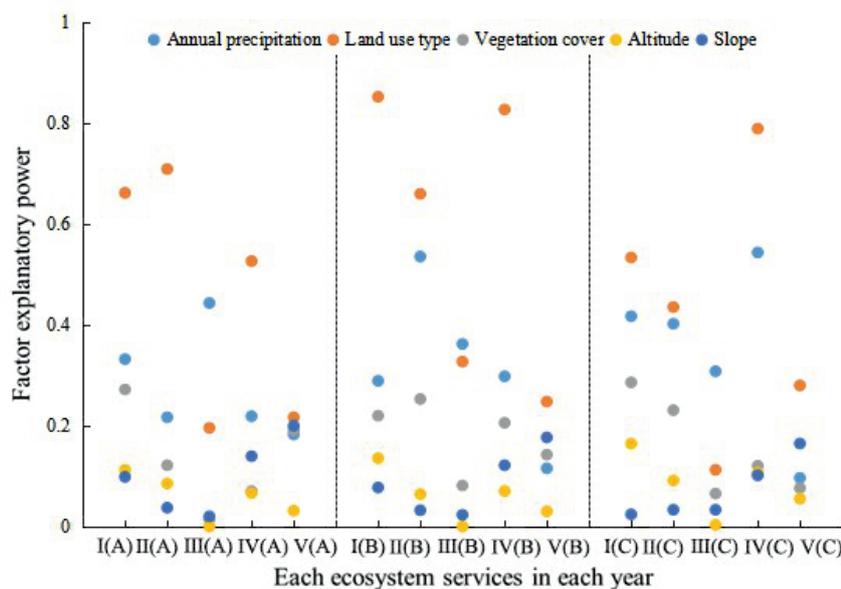


Fig. 5. Impact of driving factors on spatial heterogeneity of ecosystem services in the Yimeng mountainous area from 2000 to 2018. Note: I, II, III, IV, and V represent food supply, soil conservation, water yield, carbon storage, and habitat quality, respectively, and A, B, and C represent the years 2000, 2010, and 2018, respectively.

Table 6. Continued.

Annual precipitation-Vegetation cover	Nonlinearly enhanced	Two-factor enhancement				
Annual precipitation-Altitude	Two-factor enhancement	Two-factor enhancement	Two-factor enhancement	Nonlinearly enhanced	Two-factor enhancement	Two-factor enhancement
Annual precipitation-Slope	Two-factor enhancement					
Land use type-Vegetation cover	Two-factor enhancement	Two-factor enhancement	Two-factor enhancement	Nonlinearly enhanced	Two-factor enhancement	Two-factor enhancement
Land use type-Altitude	Two-factor enhancement	Two-factor enhancement	Two-factor enhancement	Nonlinearly enhanced	Two-factor enhancement	Two-factor enhancement
Land use type-Slope	Two-factor enhancement	Two-factor enhancement	Two-factor enhancement	Nonlinearly enhanced	Two-factor enhancement	Two-factor enhancement
Vegetation cover-Altitude	Two-factor enhancement	Nonlinearly enhanced	Nonlinearly enhanced	Two-factor enhancement	Nonlinearly enhanced	Nonlinearly enhanced
Vegetation cover-Slope	Two-factor enhancement	Nonlinearly enhanced	Nonlinearly enhanced	Nonlinearly enhanced	Two-factor enhancement	Two-factor enhancement
Altitude-Slope	Two-factor enhancement	Nonlinearly enhanced	Nonlinearly enhanced	Two-factor enhancement	Two-factor enhancement	Nonlinear enhancement
2018	Food supply	Soil conservation	Water yield	Carbon storage	Habitat quality	Habitat quality
Annual precipitation-Land use type	Nonlinearly enhanced	Two-factor enhancement	Nonlinearly enhanced	Two-factor enhancement	Two-factor enhancement	Two-factor enhancement
Annual precipitation-Vegetation cover	Two-factor enhancement	Nonlinearly enhanced	Two-factor enhancement	Two-factor enhancement	Two-factor enhancement	Two-factor enhancement
Annual precipitation-Altitude	Two-factor enhancement	Nonlinearly enhanced	Nonlinearly enhanced	Two-factor enhancement	Two-factor enhancement	Nonlinearly enhanced
Annual precipitation-Slope	Two-factor enhancement	Nonlinearly enhanced	Two-factor enhancement	Two-factor enhancement	Two-factor enhancement	Two-factor enhancement
Land use type-Vegetation cover	Two-factor enhancement					
Land use type-Altitude	Two-factor enhancement					
Land use type-Slope	Two-factor enhancement	Nonlinearly enhanced	Two-factor enhancement	Two-factor enhancement	Two-factor enhancement	Nonlinearly enhanced
Vegetation cover-Altitude	Nonlinearly enhanced	Nonlinearly enhanced	Two-factor enhancement	Two-factor enhancement	Two-factor enhancement	Nonlinearly enhanced
Vegetation cover-Slope	Nonlinearly enhanced	Nonlinearly enhanced	Nonlinearly enhanced	Two-factor enhancement	Two-factor enhancement	Two-factor enhancement
Altitude-Slope	Nonlinearly enhanced	Nonlinearly enhanced	Nonlinearly enhanced	Two-factor enhancement	Two-factor enhancement	Nonlinearly enhanced

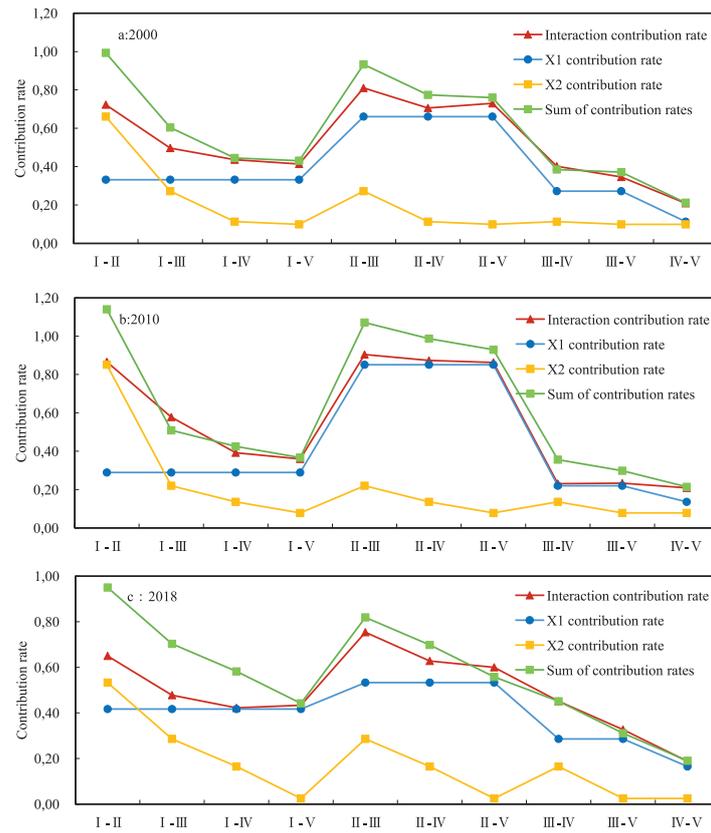


Fig. 6. Interaction contribution of food supply driving factors from 2000 to 2018.
 Note: I, II, III, IV, and V represent Annual precipitation, Land use type, Vegetation cover, Altitude, and Slope.

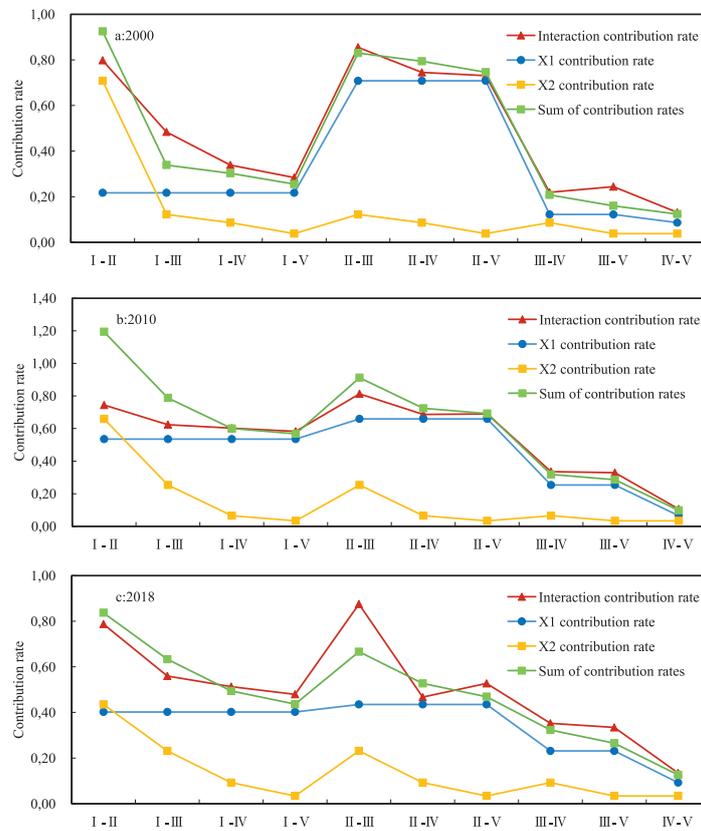


Fig. 7. Interaction contribution of soil conservation driving factors from 2000 to 2018.
 Note: I, II, III, IV, and V represent Annual precipitation, Land use type, Vegetation cover, Altitude, and Slope.

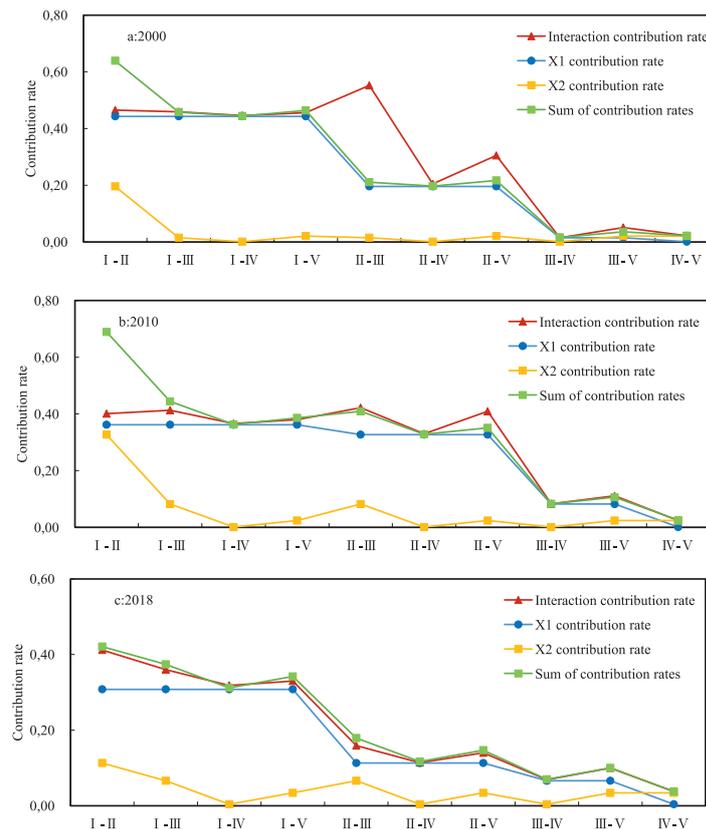


Fig. 8. Interaction contribution of water yield driving factors from 2000 to 2018.

Note: I, II, III, IV, and V represent Annual precipitation, Land use type, Vegetation cover, Altitude, and Slope.

The results of interaction detection on the spatial pattern of soil conservation (Fig. 7) showed that the interaction between land use type and other factors had the greatest influence on the spatial pattern of soil conservation, in which the land use type and annual precipitation and land use type and vegetation cover explained the soil conservation with q values above 0.7. The interaction of annual precipitation and vegetation cover with other factors also strongly explained the spatial pattern of soil conservation, with q values in the range of 0.334-0.560.

The interaction of annual precipitation with each of the other spatial factors in the water yield explains the dominant spatial pattern of water yield in the Yimeng mountainous area (Fig. 8). The interaction, denoted by the q value, of any two factors, is better than that of the single annual precipitation factor (0.308). The q value of annual precipitation and land use type reached 0.412, indicating that for the same precipitation level, different land use types can have a great impact on the spatial pattern of water yield.

Among the interaction detector results of carbon storage (Fig. 9), the interaction between land use type and other factors exerts the greatest influence on the spatial pattern of carbon storage in the Yimeng mountainous area, with the q value of land use type and annual precipitation reaching 0.891. The next factor with greater explanatory power is annual

precipitation and other factors, with q values in the range of 0.552-0.654.

As shown in Fig. 10, the interaction between land use type and other factors explained the strongest spatial pattern of habitat quality in the Yimeng mountainous area. The interaction q value of any two factors is better than that of a single annual precipitation factor (0.280). The q value of land use type and slope was the largest. The influence of slope and other factors on the spatial pattern of habitat quality was also stronger. This indicates that land use type has a significant effect on habitat quality, and the slope has a guiding effect on habitat quality.

Discussion

Spatial Heterogeneity of Ecosystem Services

The pattern is rooted in spatial heterogeneity, which forms the fundamental basis of ecological phenomena [41]. This study confirmed significant spatial heterogeneity of ecosystem services in the study area from 2000 to 2018. Among heterogeneous units, hotspot areas are mainly distributed in the east because this region is relatively inaccessible land (mostly mountainous and hilly areas) with high vegetation cover, where the growth of plants increases carbon sequestration, as well as rich plant species, better

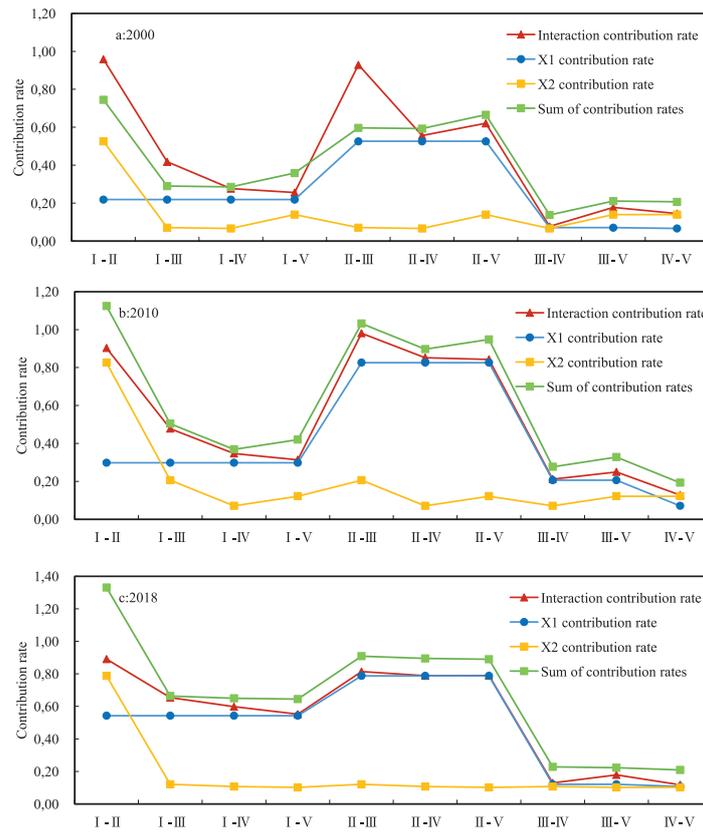


Fig. 9. Interaction contribution of carbon storage driving factors from 2000 to 2018. Note: I, II, III, IV, and V represent Annual precipitation, Land use type, Vegetation cover, Altitude, and Slope.

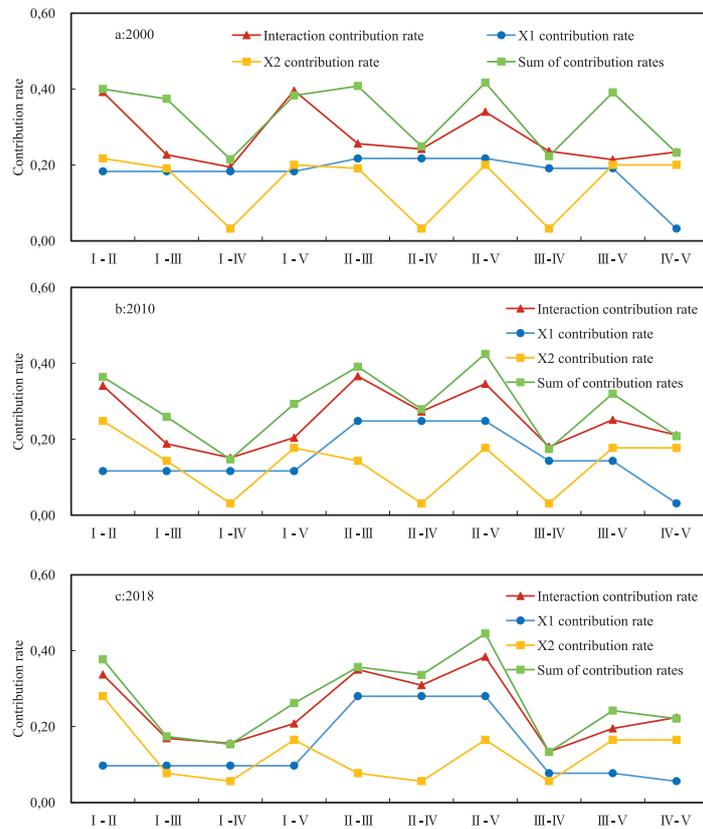


Fig. 10. Interaction contribution of habitat quality driving factors from 2000 to 2018. Note: I, II, III, IV, and V represent Annual precipitation, Land use type, Vegetation cover, Altitude, and Slope.

landscape connectivity, and higher habitat quality. At the same time, most of the garden land in the study area is also distributed in this area, and the food supply is higher. Areas with higher vegetation cover have lower water yields due to higher plant evapotranspiration. The higher vegetation cover has a higher sediment retention utility and higher soil conservation. Non-hotspot areas are mainly concentrated in the west because of the relatively flat topography of the area, the concentration of population and cities, and the lower vegetation cover, resulting in a lower food supply. Areas with lower vegetation cover and due to the effects of rapid urbanization have lower carbon storage. Related studies have also shown that the reduction in ecological land contributes most to the reduction in carbon sequestration [42-43]. Agricultural production and urban development, coupled with low vegetation cover, result in severe soil erosion and high sediment export, which leads to poor soil conservation functions. Overall, the pattern of spatial heterogeneity of ecosystem services showed a decreasing tendency from east to west.

Exploring the Mechanisms Driving the Spatial Heterogeneity of Ecosystem Services

In terms of detecting the driving mechanisms of spatial heterogeneity of ecosystem services, the Geodetector results show that spatial heterogeneity of food supply, soil conservation, and carbon storage are mainly influenced by land use type, annual precipitation, and vegetation cover, while spatial heterogeneity of water yield is mainly attributed to annual precipitation, and spatial heterogeneity of habitat quality is more likely to be influenced by land use type and slope, which is consistent with the results of existing studies in similar regions [13-14]. This indicates that the intensity of human activities on the spatial heterogeneity of ecosystem services is significantly higher than that of natural environmental factors, among which land use type is the dominant factor affecting the spatial heterogeneity of ecosystem services, and the explanatory power of the factor increases significantly after the interaction, which indicates that the spatial heterogeneity of ecosystem services in the study area is the result of the joint action of natural environmental factors and human activities, rather than a single factor playing a decisive role. In conclusion, the spatial heterogeneity of ecosystem services is caused by the natural endowment of the region, while the combination of human activities and natural geographic factors will accelerate the change in the structure and function of the regional environment and ecosystem and thus change the spatial heterogeneity of ecosystem services. Therefore, ecosystem service management needs to consider both the natural environment and human activities in an integrated manner.

Implications for Ecosystem Management Sustainably

How should we achieve ecosystem services for a sustainable state? This has been an essential concern for decision-makers worldwide. They are faced with the challenge of how to manage ecosystem services without destroying ecosystem sustainability [44]. Many studies have attempted to tackle this challenge by directly demarcating ecological conservation areas in areas that are hotspots of ecosystem services [45-46]. While improving ecosystem services to some extent, these studies fell short of considering the dissimilarity between heterogeneity units. Given this concern, exploring the factors influencing ecosystem services based on spatial heterogeneity can produce more reasonable suggestions for sustainability. The following section provides detailed recommendations for protecting ecosystem services.

The hotspot area of ecosystem services in the study area is concentrated in the mountainous hilly areas in the east because mountainous hilly areas limit human construction and development behaviours to a certain extent and provide safe spaces for forests, ensuring good capacity for providing ecosystem services. In contrast, the western region is flatter and fully exposed to human utilization, combined with the concentration of cities and human activities in the region, which makes it more vulnerable to urban expansion and the destruction wrought by human production activities and living behaviours, so most of the non-hotspot area for ecosystem services is located in this region. This feature highlights that enhancing the intensity of ecological policies in zones classified as non-hotspot areas is extremely urgent for alleviating adverse effects on ecosystem function. At the same time, the protection of ecosystem service functions in hotspot areas remains the first priority for decision-makers. In addition, our results show that land use type has the greatest impact on ecosystem services. Based on this result, we suggest that the study area should continue to prioritize ecological protection during future urban construction and economic development; continue to promote the construction of ecological security barriers; strictly implement the ecological protection red line; carry out reasonable planning of land use; reasonably coordinate the functional spaces of ecological land, urban construction land, industrial and mining land, and agricultural land; and enhance the protection of natural forests, grasslands, and wetlands throughout the region. Meanwhile, the ecologically fragile areas that have been affected by construction and industrial and mining activities are restored and rebuilt by measures such as returning farmland to forests and grasses and closure and management of large areas.

Limitations and Generalization Contributions

This study proposes a new way of studying the driving mechanism of ecosystem services from the perspective of spatial heterogeneity. It not only provides a new dimension to spatially identify the dominant factors and combinations of factors that affect ecosystem services but also quantitatively describes their contribution. In addition, this study explores the interrelationships among ecosystem services for the sustainable development of local ecosystems. However, there were still some limitations and uncertainties for further improvement. First, the interaction analysis by Geodetector can involve only two drivers, which may not be sufficient to reflect the combined contribution of various factors. Second, the present study only analysed the main influencing factors of the spatial heterogeneity of ecosystem services at the global scale, but the main influencing factors of ecosystem services may differ at different spatial scales, so the attribution analysis is far from thorough.

Despite some shortcomings, this study attempts to gain a deeper understanding of the mechanisms driving the spatial heterogeneity of ecosystem services. In contrast to traditional analysis methods that provide only statistical results, this study uses a quantitative descriptive approach to identify the drivers and combinations of factors that have a major impact on the spatial heterogeneity of ecosystem services. Subsequently, an in-depth study of the drivers of the spatial heterogeneity of ecosystem services, combined with the interrelationships among ecosystem services, provides more theoretical and practical advice to local decision-makers. In addition, the data and methods mentioned in this study could also be applied to other regions in the world and it was also a case study and reference for ecological management, especially in complex mountainous hilly areas.

Conclusions

This article provides a new way of thinking for the study of attribution analysis of the spatial heterogeneity of ecosystem services. Full consideration of the spatial heterogeneity of ecosystem services reveals the direct and indirect driving mechanisms of the spatial heterogeneity of ecosystem services, which has not received sufficient attention in previous research. First, in this paper, the InVEST model and RUSLE model were used to estimate ecosystem services in the Yimeng mountainous area from 2000 to 2018. Then, through spatial analysis, it was found that the ecosystem services in the study area were characterized by significant spatial heterogeneity with an uneven east-west distribution. Furthermore, we further explored the drivers affecting the spatial heterogeneity of ecosystem services. In the study of the role of drivers, we found that land use type was the dominant factor influencing

the spatial heterogeneity of ecosystem services and that the combined effect of multiple drivers was more significant than that of any single driver in the interaction mechanism. This highlights the importance of land-use management for ecosystem services and the need for integrated consideration of multifactor coupling mechanisms for ecosystem service management. These conclusions are of great relevance to the development of targeted spatial planning decisions for ecosystem services in the Yimeng mountainous area and provide guidance for subsequent activities and policies in other similar areas.

Acknowledgments

This work was supported by the Shandong Province College Youth Innovation Science and Technology Support Program [2019KJH001].

Conflict of Interest

The authors declare that they have no conflict of interest.

Reference

1. COSTANZA R., D' ARGE R., DE GROOT R., FARBER S., GRASSO M., HANNON B., LIMBURG K., NAEEM S., ONEILL R. V., PARUELO J., RASKIN R.G., SUTTON P. The value of the world's ecosystem services and natural capital. *Nature*. **387** (15), 255, **1997**.
2. POTSCHIN M.B., HAINESYOUNG R.H. Ecosystem services. *Prog. Phys. Geog.* **35** (5), 575, **2011**.
3. TENGBERG A., FREDHOLM S., ELIASSON I., KNEZ I., SALTZMAN K., WETTERBERG O. Cultural ecosystem services provided by landscapes: assessment of heritage values and identity. *Ecosystem Services*. **2**, 14, **2012**.
4. CHEN M.Y., GAO B.J., LIU S.H., ZHOU G.N. Response of ecosystem service value to changes in ecosystem structure. *Polish Journal of Environmental Studies*. **28** (4), 2089, **2019**.
5. YAO T.D., QIN D.H., SHEN Y.P., ZHAO L., LU A.X. Cryospheric changes and their impacts on regional water cycle and ecological conditions in the qinghai-tibetan plateau. *Chinese Journal of Nature*. **35** (03), 179, **2013** [In Chinese].
6. ZHANG X.M., WANG K.L., YUE Y.M., TONG X.W., LIAO C.J., ZHANG M.Y., JIANG Y. Factors impacting on vegetation dynamics and spatial non-stationary relationships in karst regions of southwest China. *Acta Ecologica Sinica*. **37** (12), 4008, **2017** [In Chinese].
7. ZHAI T. L., WANG J., JIN Z. F., QI Y., FANG Y., LIU J. Did improvements of ecosystem services supply-demand imbalance change environmental spatial injustices? *Ecological Indicators*. **111**, 106068, **2020**.
8. GAO J.B., ZUO L.Y., WANG H. The spatial trade-offs and differentiation characteristics of ecosystem services in karst peak-cluster depression. *Acta Ecologica Sinica*. **39** (21), 7829, **2019** [In Chinese].

9. AJAZ AHMED M.A., ABD-ELRAHMAN A., ESCOBEDO F.J., CROPPER W.P., MARTIN T.A., TIMILSINA N. Spatially-explicit modeling of multi-scale drivers of aboveground forest biomass and water yield in watersheds of the southeastern United States. *Journal of Environmental Management*. **199**, 158, **2017**.
10. HOU W.J., GAO J.B., DAI E.F., PENG T., WU S.H. The runoff generation simulation and its spatial variation analysis in Sanchahe basin as the south source of Wujiang. *Acta Geographica Sinica*. **73** (7), 1268, **2018** [In Chinese].
11. PENG J., TIAN L., ZHANG Z.M., ZHAO Y., GREEN S.M., QUINE T.A., LIU H.Y., MEERSMANS J. Distinguishing the impacts of land use and climate change on ecosystem services in a karst landscape in China. *Ecosystem Services*. **46**, 101199, **2020**.
12. WANG Y., ZHAO J., FU J., WEI W. Effects of the Grain for Green Program on the water ecosystem services in an arid area of China -using the Shiyang River Basin as an example. *Ecological Indicators*. **104**, 659, **2019**.
13. WANG Y.H., DAI E.F., GE Q.S., ZHANG X.Z., YU C.Q. Spatial heterogeneity of ecosystem services and their trade-offs in the Hengdian Mountain region, Southwest China. *Catena*. **207**, 105632, **2021**.
14. GAO J.B., ZUO L.Y., LIU W.L. Environmental determinants impacting the spatial heterogeneity of karst ecosystem services in Southwest China. *Land Degradation & Development*. **32** (4), 1718, **2020**.
15. WANG J.F., XU C.D. Geodetector: Principle and prospective. *Acta Geographica Sinica*, **72** (1), 16, **2017** [In Chinese].
16. TURNER M.G., DONATO D.C., ROMME W.H. Consequences of spatial heterogeneity for ecosystem services in changing forest landscapes: Priorities for future research. *Landscape Ecology*. **28** (6), 1081, **2012**.
17. HASSAN R., SCHOLES R., ASH N. *Ecosystems and Human Well-being: Current State and Trends*. Washington, DC: Island Press. **2005**.
18. Ministry of Environmental Protection of the People's Republic of China. *National ecological function zoning (revised edition)*. Beijing: Ministry of Environmental Protection of the People's Republic of China. **2015** [In Chinese].
19. THE STATE COUNCIL OF THE PEOPLE'S REPUBLIC OF CHINA. *The National Outline of Ecological Environment Conservation*. Beijing: The State Council of the People's Republic of China. **2000** [In Chinese].
20. WU W.H., PENG J., LIU Y., HU Y.N. Tradeoffs and synergies between ecosystem services in Ordos City. *Progress in Geography*. **36** (12), 1571, **2016** [In Chinese].
21. ARONOLDUS H.M.J. An approximation of the rainfall factor in the Universal Soil Loss Equation. An approximation of the rainfall factor in the Universal Soil Loss Equation. **127**, **1980**.
22. WILLIAMS J.C.M., KING K.A., NEARING M.A. Using soil erosion models for global change studies. *Journal of Soil and Water Conservation*. **51** (5), 381, **1996**.
23. WISCHMEIER W.H., SMITH D.D. Predicting rainfall erosion losses. *Agriculture Handbook*. **537**, 285, **1987**.
24. MCCOOL D.K., FOSTER G.R., MUTCHLER C.K., MEYER L. D. Revised slope length factor for the universal soil loss equation. *Transactions of the ASABE*. **32** (5), 1571, **1989**.
25. LIU B.Y., NEARING M.A., SHI P.J., JIA Z.W. Slope length effects on soil loss for steep slopes. *Soil Science Society of America Journal*. **64**(5), 1759, **2000**.
26. CAI C.F., DING S.W., SHI Z.H., HUANG L., ZHANG G.Y. Study of applying USLE and geographical information system IDRISI to predict soil erosion in small watershed. *Journal of Water and Soil Conservation*. **14** (2), 19, **2016** [In Chinese].
27. SHARP R., DOUGLASS J., WOLNY S., ARKEMA K., BERNHARDT J., BIERBOWER W., CHAUMONT N., DENU D., FISHER D., GLOWINSKI K., GRIFFIN R., GUANNELL G., GUERRY A., JOHNSON J., HAMEL P., KENNEDY C., KIM C.K., LACAYO M., LONSDORF E., MANDLE L., ROGERS L., SILVER J., TOFT J., VERUTES G., VOGL A.L., WOOD S., WYATT K. InVEST 3.9.0.post72+ug.ga7792a3 User's Guide. The Natural Capital Project, Stanford University, University of Minnesota, The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund. **2020**.
28. LU H.T., YAN Y., ZHU J.Y., JIN T.T., LIU G.H., WU G., STRINGER L.C., DALLIMER M. Spatiotemporal water yield variations and influencing in the Lhasa River basin, Tibetan Plateau. *Water*. **12** (5), 1498, **2020**.
29. YIN G.D., WANG X., ZHANG X., FU Y.S., HAO F.H., HU Q.H. InVEST Model-Based Estimation of Water Yield in North China and Its Sensitivities to Climate Variables. *Water*. **12** (6), 1692, **2020**.
30. WANG L.G., ZHU R., YIN Z.L., CHEN Z.X., FANG C.S., LU R., ZHOU J.Q., FENG Y.L. Impacts of land-Use change on the spatio-temporal patterns of terrestrial ecosystem carbon storage in the Gansu Province, Northwest China. *Remote Sensing*. **14** (13), 3164, **2022**.
31. XIANG S.J., WANG Y., DENG H., YANG C.M., WANG Z.F., GAO M. Response and multi-scenario prediction of carbon storage to land use/cover change in the main urban area of Chongqing, China. *Ecological Indicators*. **142**, **2022**.
32. WEI Q.Q., ABUDUREHEMAN M., HALIKE A., YAO K.X., YAO L., TANG H., TUHETI B. Temporal and spatial variation analysis of habitat quality on the PLUS-InVEST model for Ebinur Lake Basin, China. *Ecological Indicators*. **145**, **2022**.
33. WU L.L., SUN C., FAN F.L. Estimating the characteristic spatiotemporal variation in habitat quality using the InVEST model-A case study from Guangdong-Hong Kong-Macao Greater Bay Area. *Remote Sensing*. **13** (5), 1008, **2021**.
34. JING H.C., LIU Y.H., HE P., ZHANG J.Q., DONG J.Y., WANG Y. Spatial heterogeneity of ecosystem services and its influencing factors in typical areas of the Qinghai-Tibet Plateau: A case study of Nagqu City. *Acta Ecologica Sinica*. **42** (7), 2657, **2022** [In Chinese].
35. XU C.X., GONG J., LI Y., YAN L.L., GAO B.L. Spatial distribution characteristics of typical ecosystem services based on terrain gradients of Bailongjiang Watershed in Gansu. *Acta Ecologica Sinica*. **40** (13), 4291, **2020** [In Chinese].
36. PENG J., HU X. X., QIU S. J., HU Y. N., MEERSMANS J., LIU Y. X. Multifunctional landscapes identification and associated development zoning in mountainous area. *Science of the Total Environment*. **660**, 765, **2019**.
37. ZHENG Z.M., FU B.J., HU H.T., GE S. A method to identify the variable ecosystem services relationship across time: a case study on Yanhe Basin, China. *Landscape Ecol*. **29** (10), 1689, **2014**.
38. YUAN J., LI R., HUANG K. Driving factors of the variation of ecosystem service and the trade-off and

- synergistic relationships in typical karst basin. *Ecological Indicators*. **142**, 2022.
39. CHEN T.Q., FENG Z., ZHAO H.F., WU K.N. Identification of ecosystem service bundles and driving factors in Beijing and its surrounding areas. *Science of the Total Environment*. **711** (2), 134687, 2020.
40. JI J.W., WANG S.X., ZHOU Y., LIU W.L., WANG L.T. Studying the Eco-Environmental Quality Variations of Jing-Jin-Ji Urban Agglomeration and Its Driving Factors in Different Ecosystem Service Regions From 2001 to 2015. *IEEE ACCESS*. **8**, 154940, 2020.
41. WU J.G. Effects of changing scale on landscape pattern analysis: scaling relations. *Landscape Ecology*. **19**(2), 125, 2004.
42. WANG C., LIU C.F., WU Y.H., LIU Y.Y. Spatial pattern, tradeoffs and synergies of ecosystem services in loess hilly region: A case study in Yuzhong County. *Chinese Journal of Ecology*. **38**(2), 521, 2019.
43. LIU H.Y., XIAO W.F., LI Q., TIAN Y., ZHANG Q.R., ZHU J.H. Spatiotemporal variations and trade-offs of ecosystem services in Beijing. *Chinese Journal of Ecology*. **40** (1), 209, 2021.
44. ZHANG Y., LIU Y.F., ZHANG Y., LIU Y., ZHANG G.X., CHEN Y.Y. On the spatial relationship between ecosystem services and urbanization: A case study in Wuhan, China. *Science of the Total Environment*. **637**, 2018.
45. ROSSI P., PECCI A., AMADIO V., ROSSI O., SOLIANI L. Coupling indicators of ecological value and ecological sensitivity with indicators of demographic pressure in the demarcation of new areas to be protected: The case of the Oltrepò Pavese and the Ligurian-Emilian Apennine area (Italy). *Landscape and Urban Planning*. **85** (1), 12, 2008.
46. ZHUANG Z.Z., LI K.Y., LIU J.X., CHENG Q.W., GAO Y., SHAN J.X., CAI L.Y., HUANG Q.H., CHEN Y.M., CHEN D. China's New Urban Space Regulation Policies: A Study of Urban Development Boundary Delineations. *Sustainability*, **9** (1), 45, 2016.